Flavor Structure beyond the Standard Model

Matthias Neubert

Institute for Physics, Johannes Gutenberg University Mainz &
Institute for Theoretical Physics, University of Heidelberg

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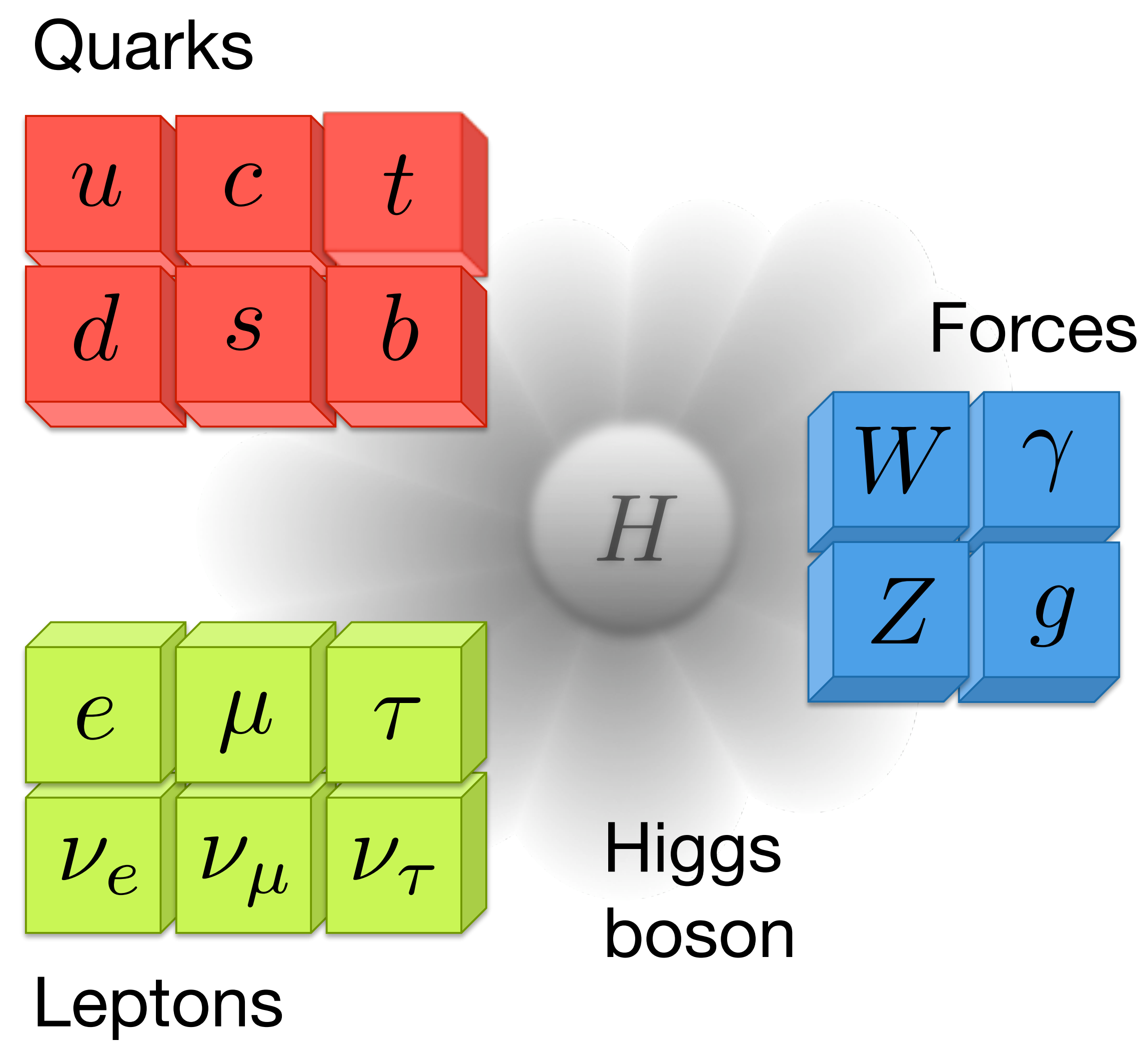
Standard Model and Beyond

Fundamental laws derived from few, basic guiding principles:

- Symmetries (gauge theories)
- Simplicity and beauty (few parameters)
- Naturalness (avoid fine-tuning)
- Anarchy (everything is allowed)

Standard Model of particle physics:

- works beautifully, explaining all experimental phenomena with great precision
- no compelling hints for deviations
- triumph of 20th century science



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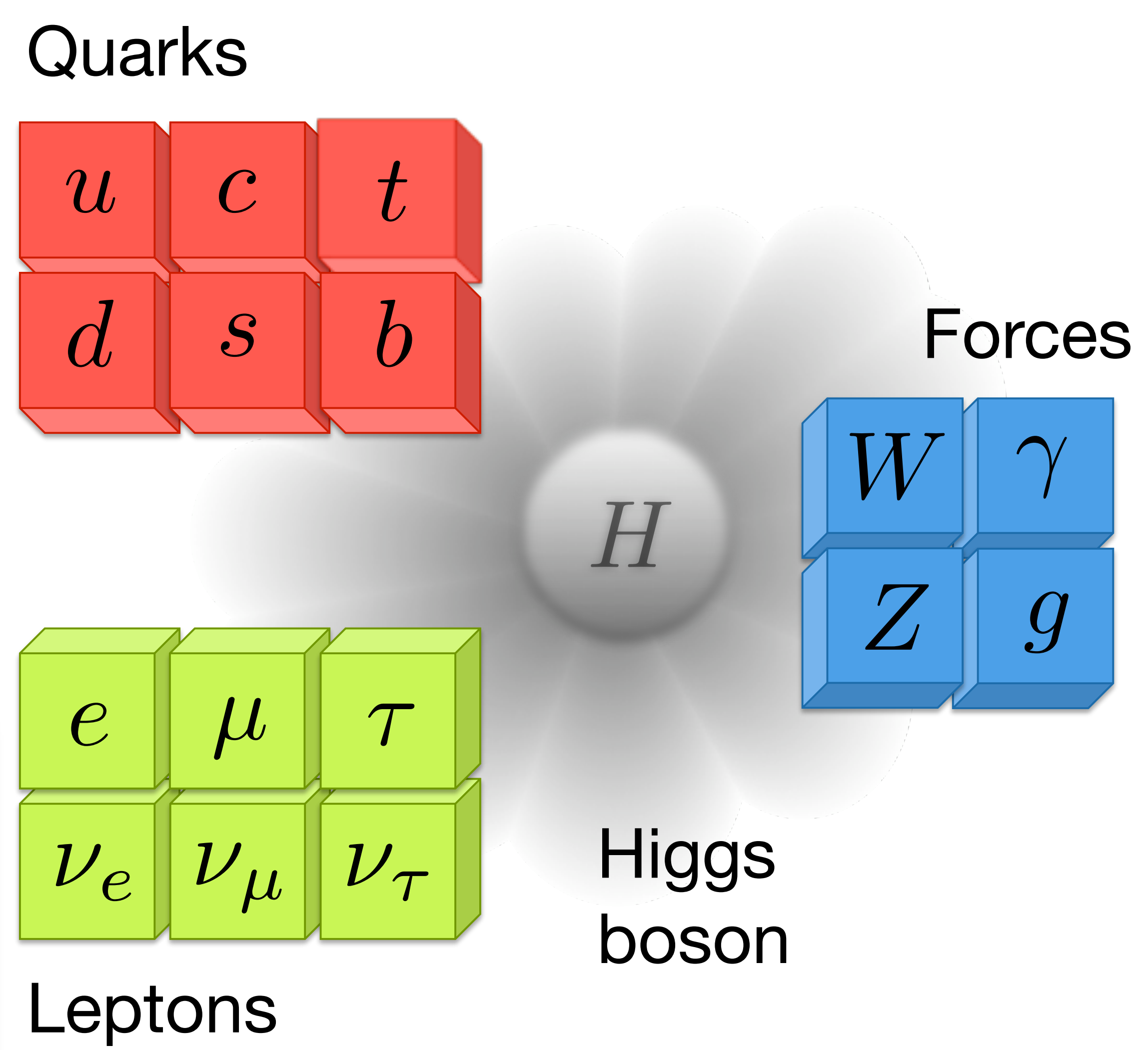

But many questions remain unanswered:

- Origin of generations and structure of Yukawa interactions?
- Matter-antimatter asymmetry?
- Unification of forces? Neutrino masses?
- Dark matter and dark energy?

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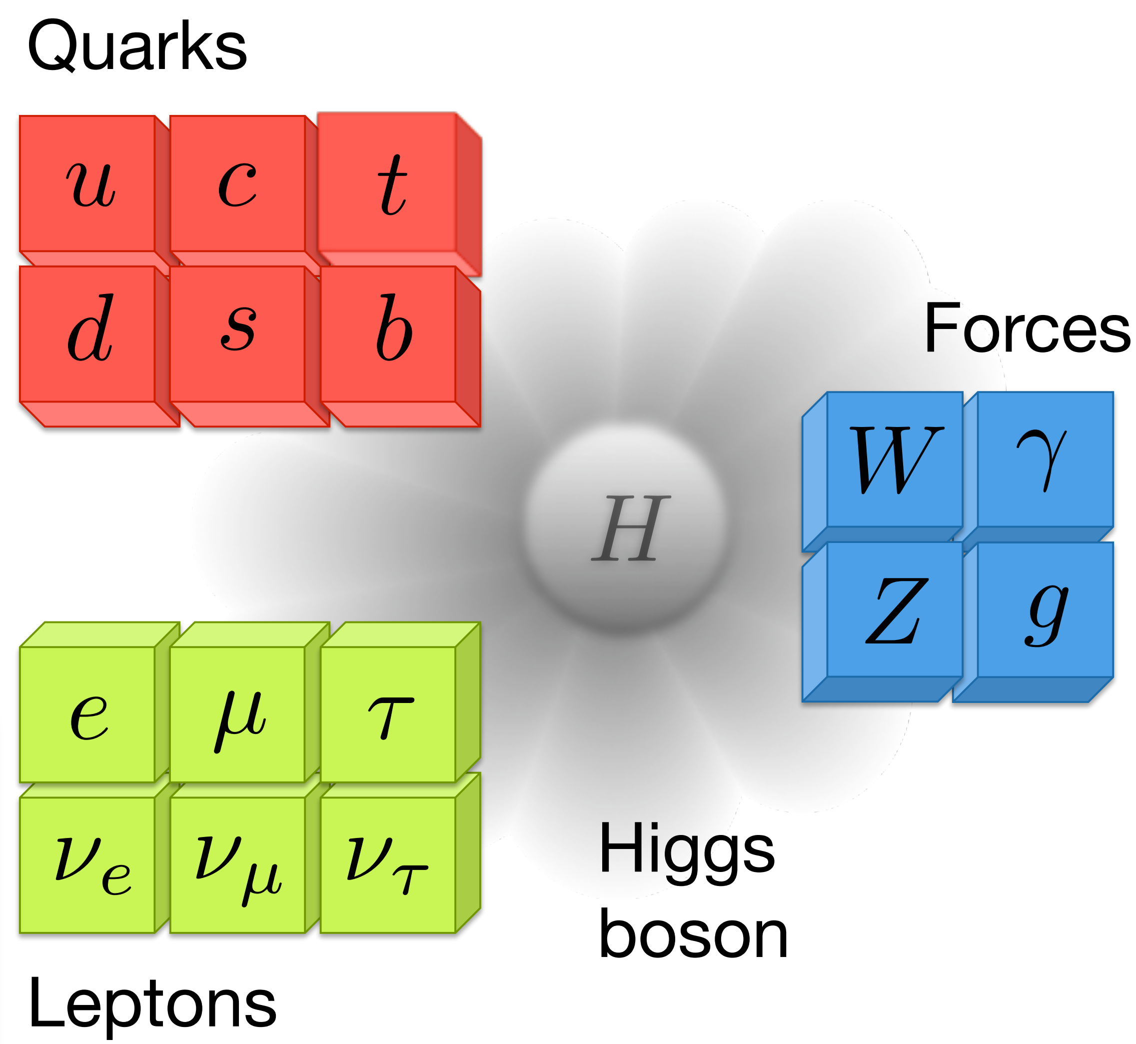
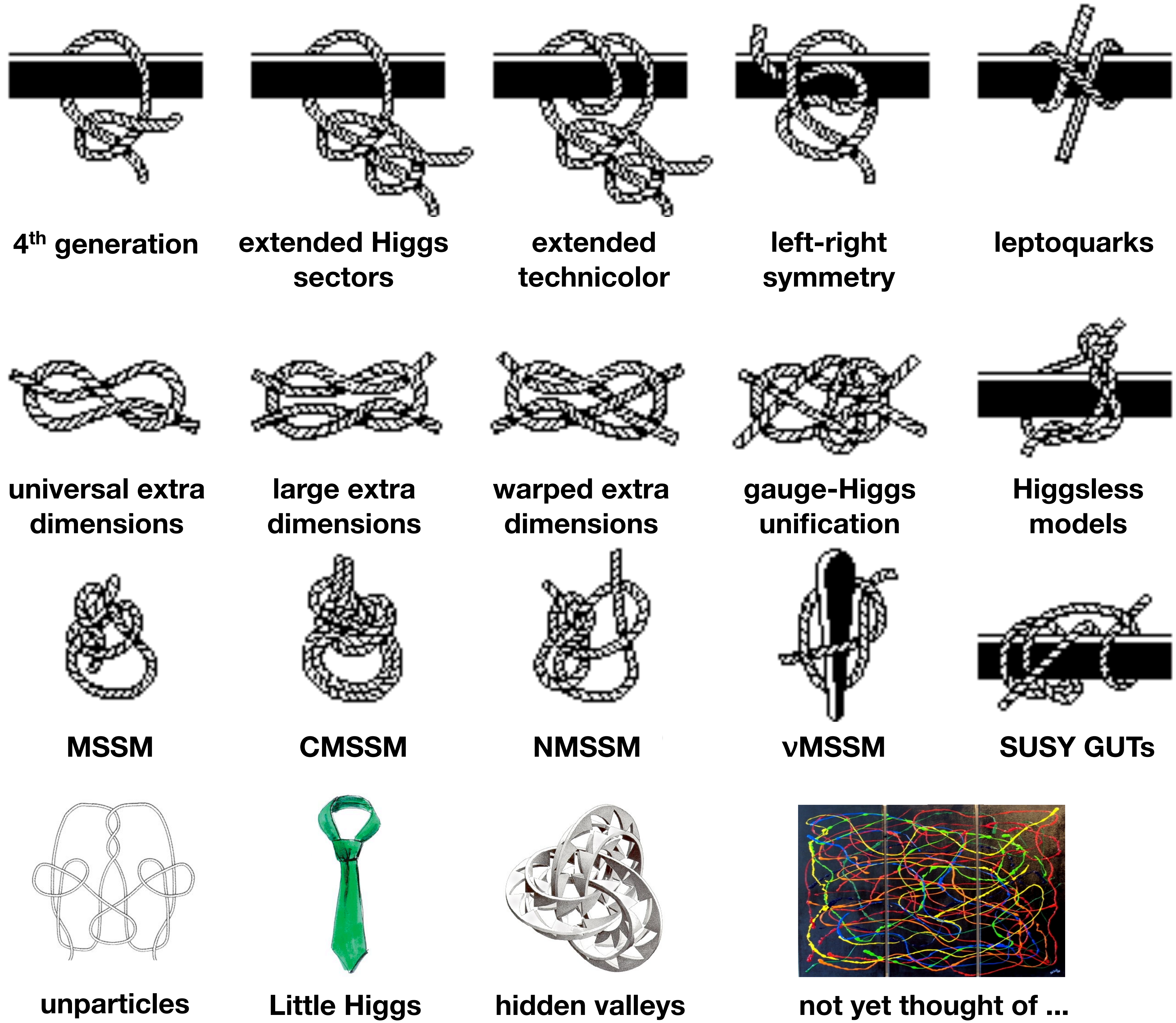


Strong prejudice that there must be "New Physics"

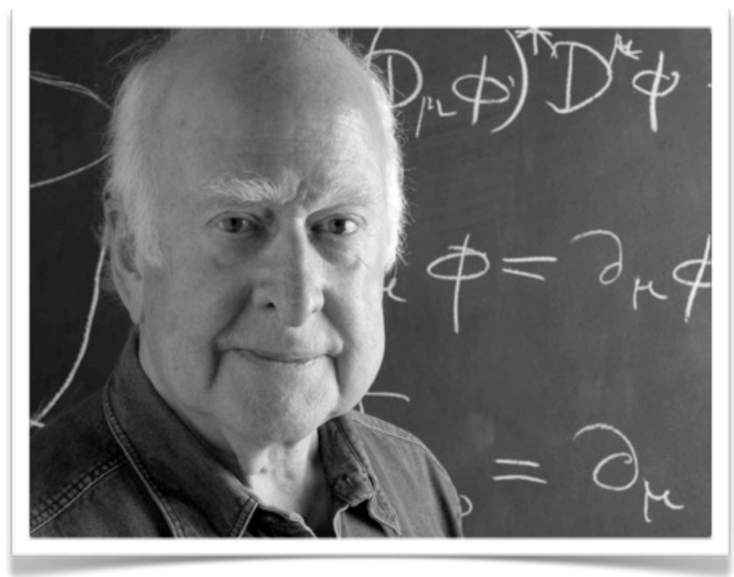
Standard Model and Beyond: The Gordian Knot

What is the “New Physics” and how to find it ?

Standard Model and Beyond

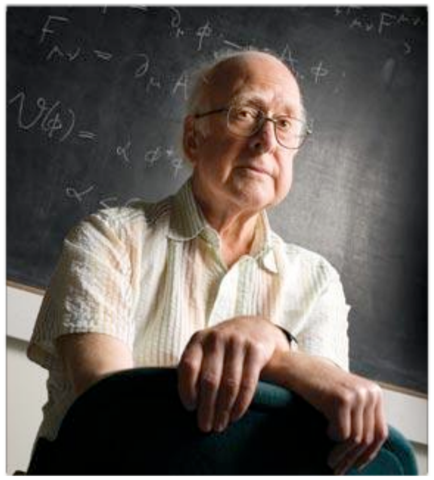


Standard Model and Beyond



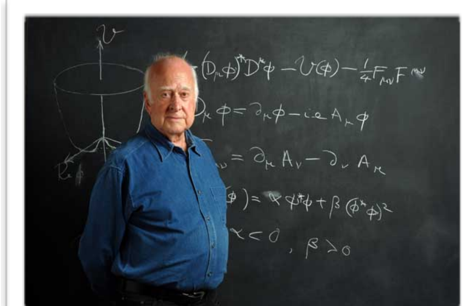
Which Higgs ?

Standard Model and Beyond

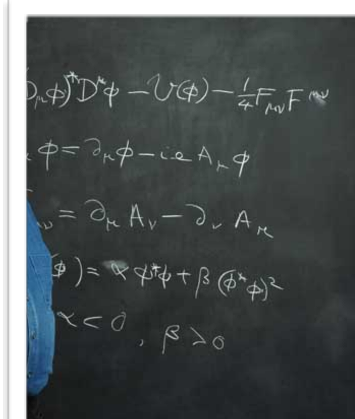


gauge-phobic Higgs

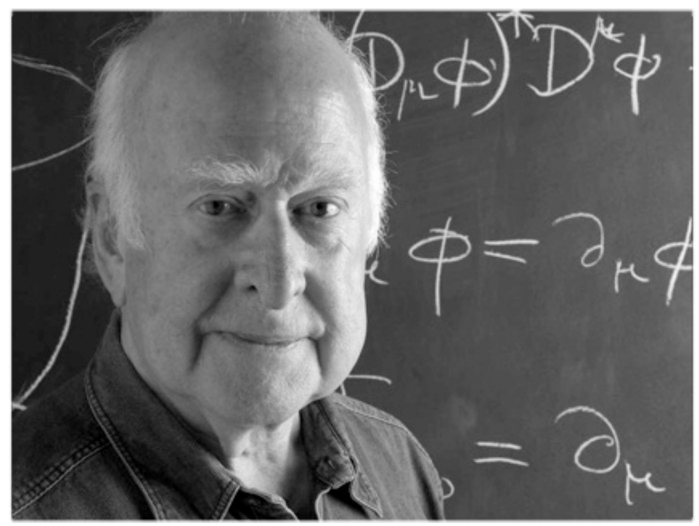
composite Higgs



little Higgs

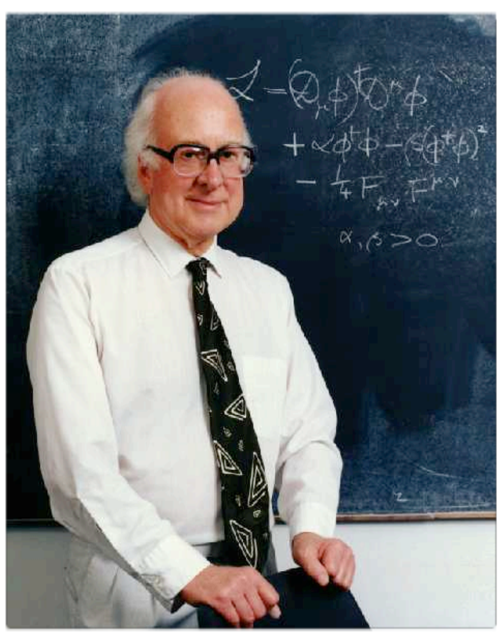


invisible Higgs



Which Higgs ?

private Higgs



charming Higgs

the God particle

burried Higgs

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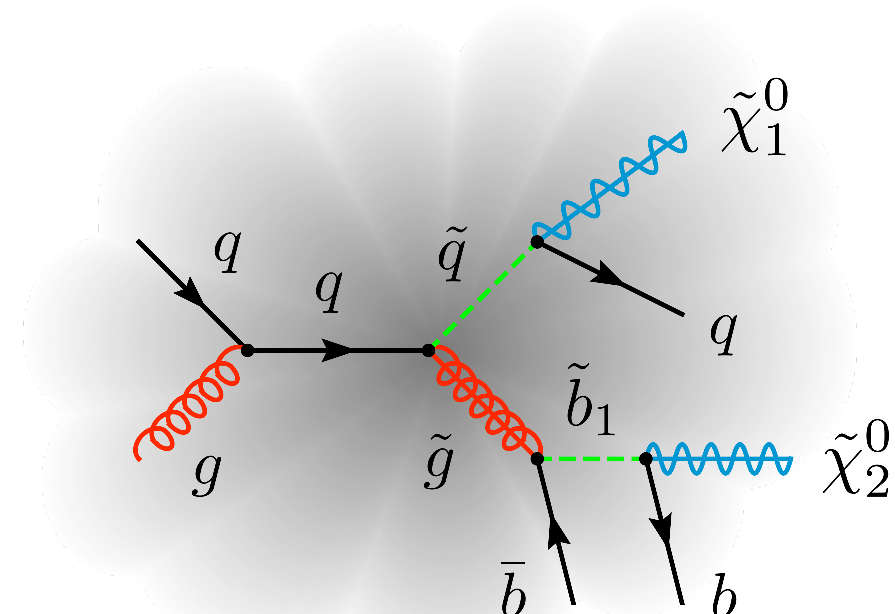
Searches for New Physics: Energy Frontier

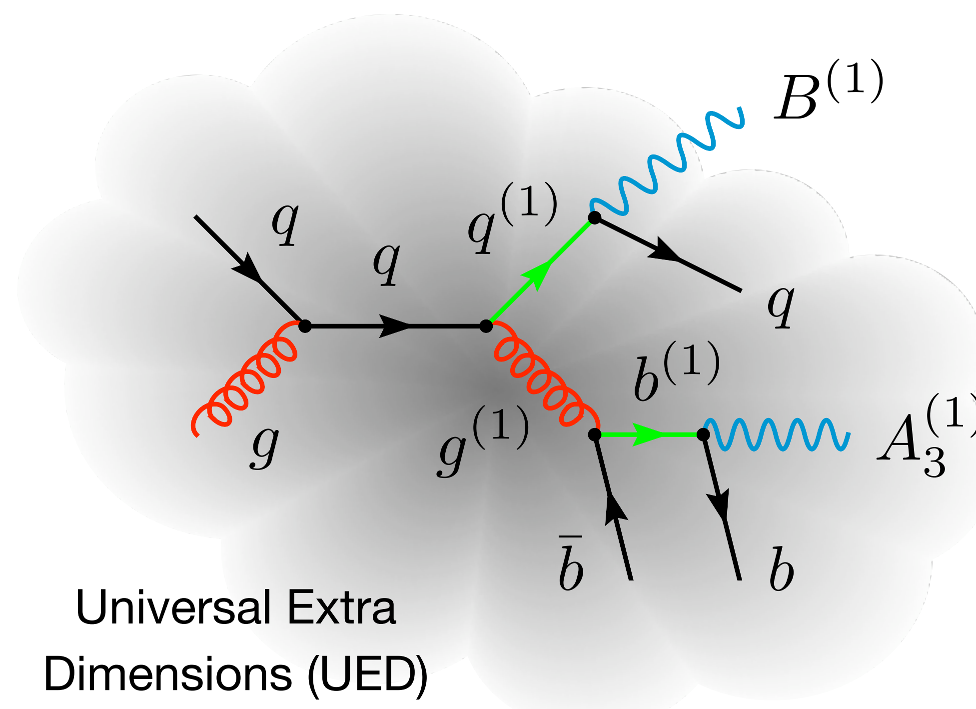
Production of new particles at high-energy colliders probes directly the structure of matter and its interactions:

- Charm at BNL, SLAC (1974)
- Bottom by E288 at FNAL (1977)
- W, Z bosons by UA1/2 at CERN (1983)
- Top by CDF, DØ at FNAL (1995)
- Higgs at FNAL (?), CERN (?), ...

However, quite different scenarios of New Physics can lead to very similar signatures and hence to experimental signals that are difficult to disentangle



Minimal supersymmetric SM (MSSM)



Universal Extra Dimensions (UED)

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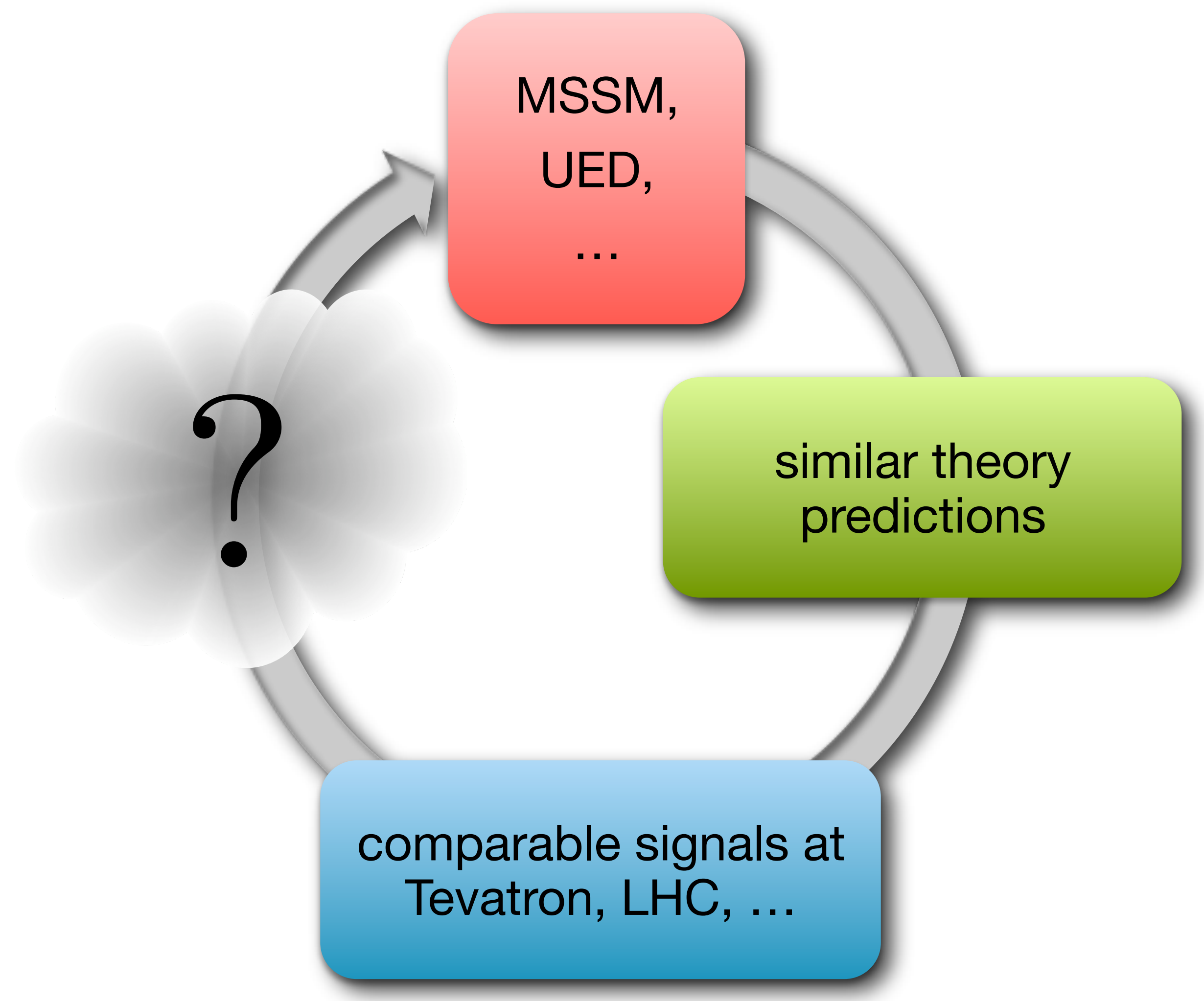


LHC inverse problem

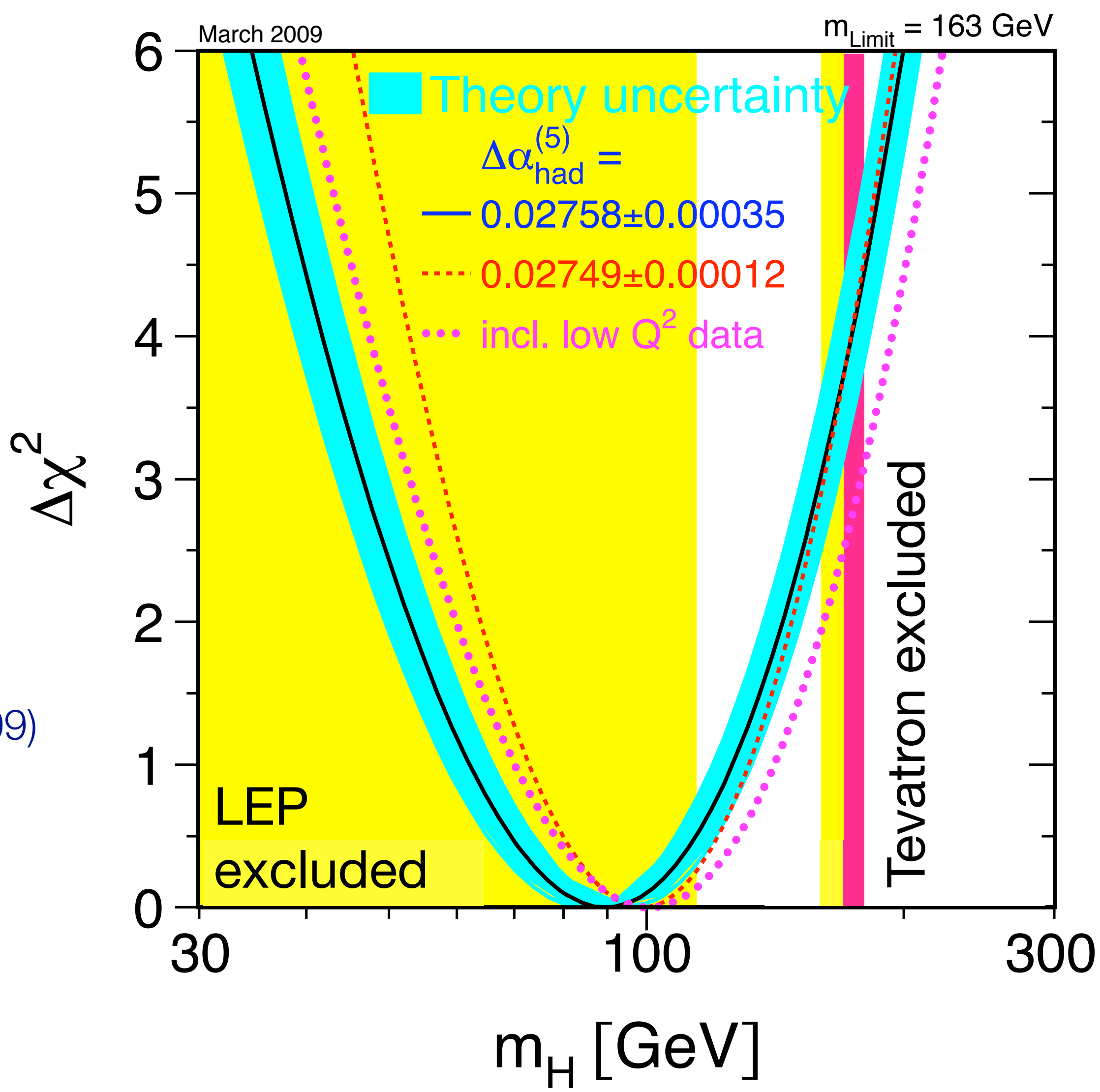
Searches for New Physics: Intensity Frontier

Low-energy experiments at high luminosity study effects resulting from virtual particle exchange:

- Charm mass from K–$\overline{K}$ mixing
- Top mass from B–$\overline{B}$ mixing, precision measurements at Z pole
- Higgs mass from electroweak precision observables
- hints for New Physics in $(g\text{-}2)_\mu$:
  $a_\mu^{exp} - a_\mu^{SM} = (290 \pm 90) \cdot 10^{-11}$
  Jegerlehner, Nyffeler (2009)

Offers indirect insights into the structure of matter and its interactions at quantum level

Indirect constraints on the Higgs mass:



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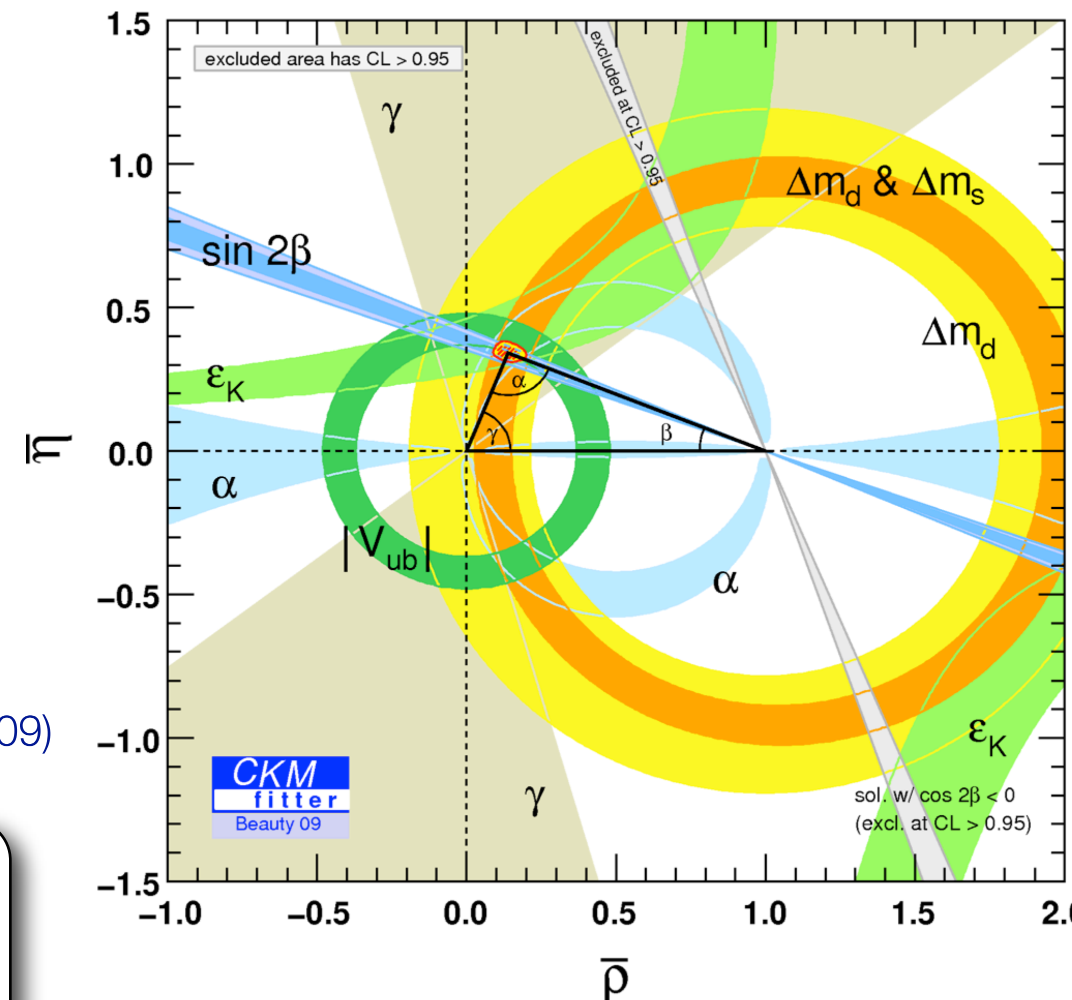
Provides sensitivity to energy regimes and probes aspects of couplings not accessible to direct searches, paving the way for discoveries or constraints of New Physics

Global analysis of the unitarity triangle:



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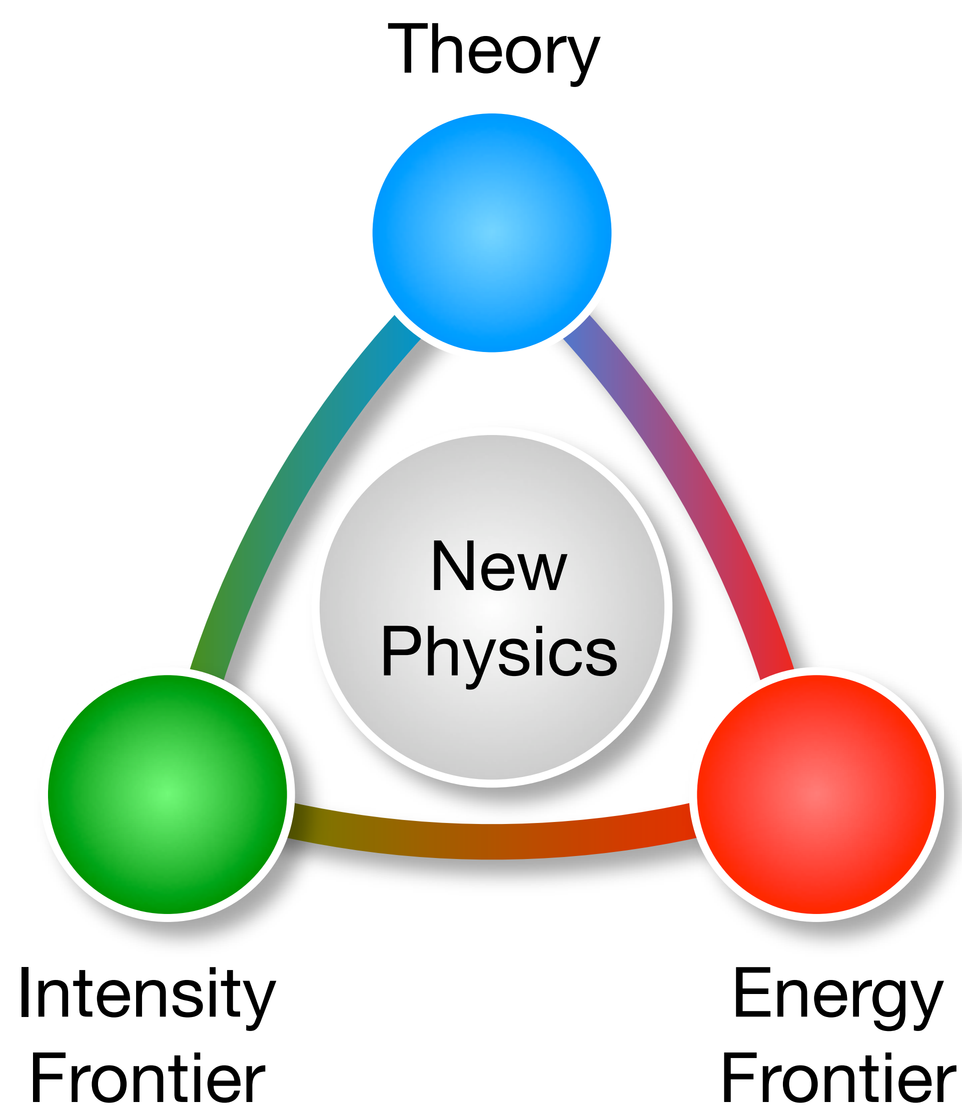
Searches for New Physics: Interplay

Complementarity and synergy:

Answering the open questions of elementary particle physics requires a joint effort:

- Theory: precision calculations in the SM, studies of New Physics, model-building, ...
- High-energy experiments: Tevatron, LHC, ILC (?), CLIC (?), Muon Collider (?), ...
- Low-energy experiments: BaBar, Belle, Super-*B*, NA62, J-PARC, Project X, neutrino physics, EDMs, $(g-2)_\mu$, ...



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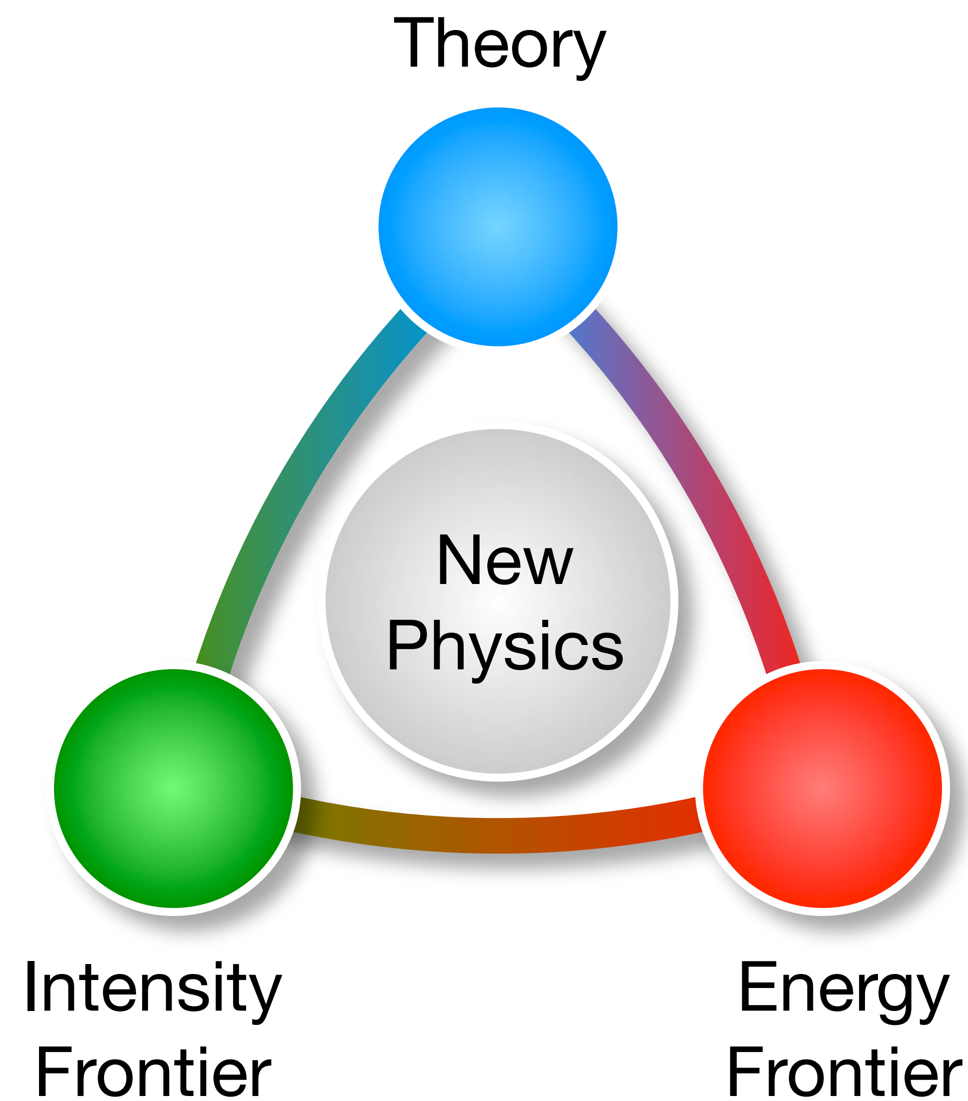
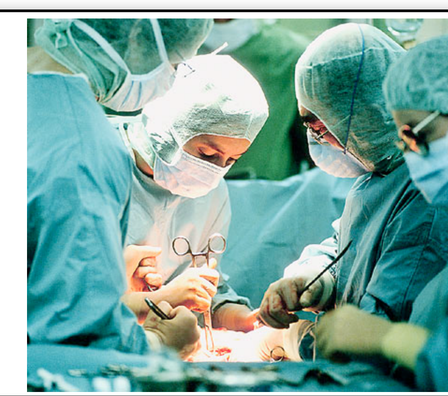


Quark flavor physics is a crucial component in this program, which provides surgical probes of subtle corrections to fundamental interactions

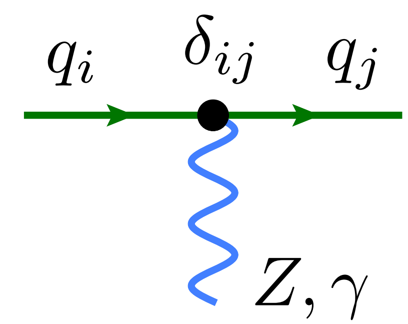


Flavor Structure in the SM and Beyond

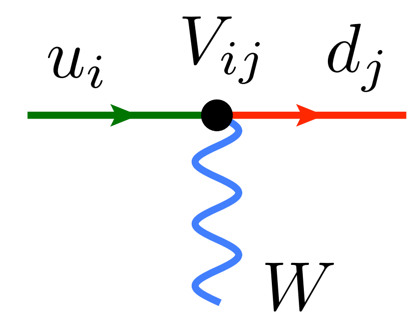
Flavor physics means phenomena related to Yukawa couplings and generation-changing interactions in the fermion sector

In SM:

- all flavor-violating interactions encoded in Yukawa couplings to Higgs boson
- suppression of flavor-changing neutral currents (FCNCs) and CP violation in quark sector due to unitarity of CKM matrix, small mixing angles, and GIM mechanism



δ: unit matrix



V: CKM matrix

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \boldsymbol{V} \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

$\lambda \approx 0.22$, Cabibbo angle

N. Cabibbo

M. Kobayashi

T. Maskawa

Nobel Price in Physics 2008 for Kobayashi & Maskawa

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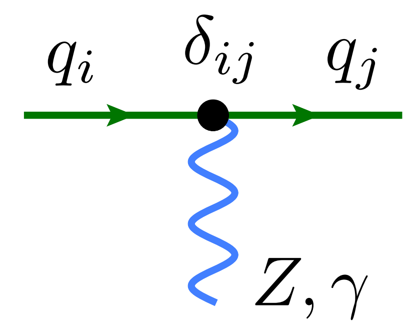

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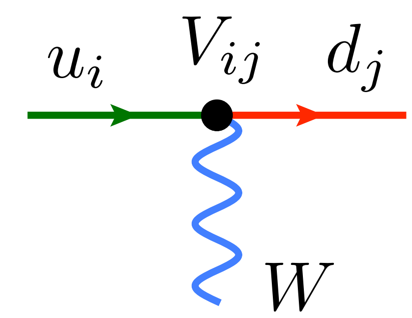

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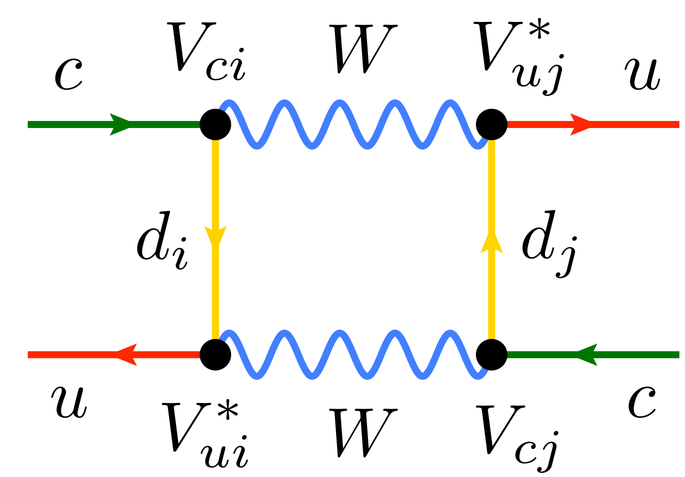


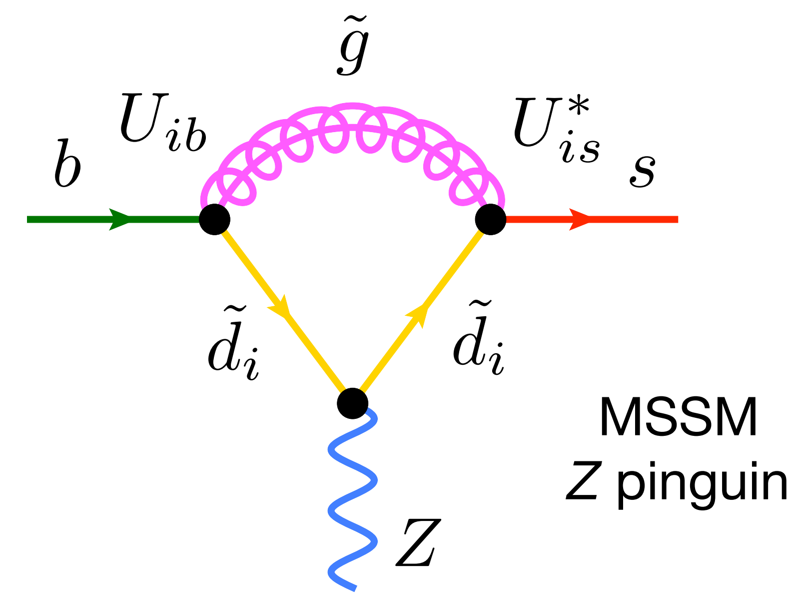
$$\boxed{\sum_{i,j} \lambda_i \lambda_j \, f(m_i, m_j) \approx \lambda_b^2 \, \frac{m_b^2 - m_d^2}{M_W^2} + \lambda_s^2 \, \frac{m_s^2 - m_d^2}{M_W^2} \approx \lambda_b^2 \, \frac{m_b^2}{M_W^2} \,, \quad \lambda_i \equiv V_{ui}^* V_{ci}}$$

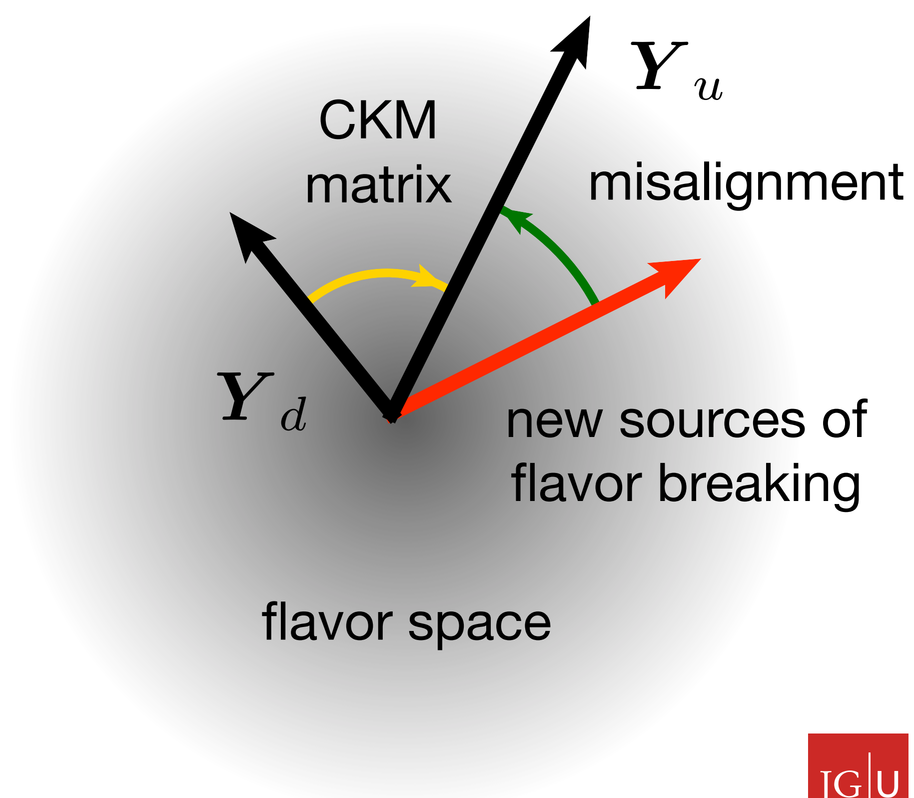
Flavor Structure in the SM and Beyond

In extensions of SM, additional flavor and CP violation can arise from exchange of new scalar (H^+, $\tilde{q}$, ...), fermionic ($\tilde{g}$, t', $t^{(1)}$, ...), or gauge (Z', $g^{(1)}$, ...) degrees of freedom

- new flavor-violating terms in general not aligned with SM Yukawa couplings $\boldsymbol{Y}_u$, $\boldsymbol{Y}_d$
- can lead to excessive FCNCs, unless:
  - new particles are heavy: $\tilde{m}_i >> 1$ TeV
  - masses are degenerate: $\Delta\tilde{m}_{ij} << \tilde{m}_i$
  - mixing angles are very small: $U_{ij} << 1$

Absence of clear New Physics signals in FCNCs implies strong constraints on flavor structure of TeV-scale physics (if it exists)



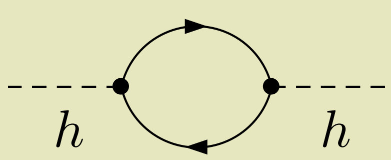


Flavor Structure in the SM and Beyond

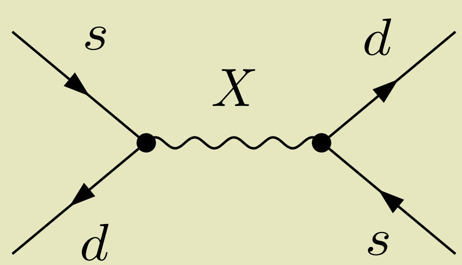
$$\mathcal{L}_{\rm EFT} = \underbrace{\boxed{\Lambda_{\rm UV}^2\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2}} + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \underbrace{\boxed{\frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}}} + \boxed{\frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2}}} + \dots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

$\Downarrow$



$$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\rm UV}^2$$



$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\qquad\qquad$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

Possible solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

(i) $\Lambda_{\rm UV} >> 1$ TeV: Higgs fine tuned, new particles too heavy for LHC

(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a flavor symmetry

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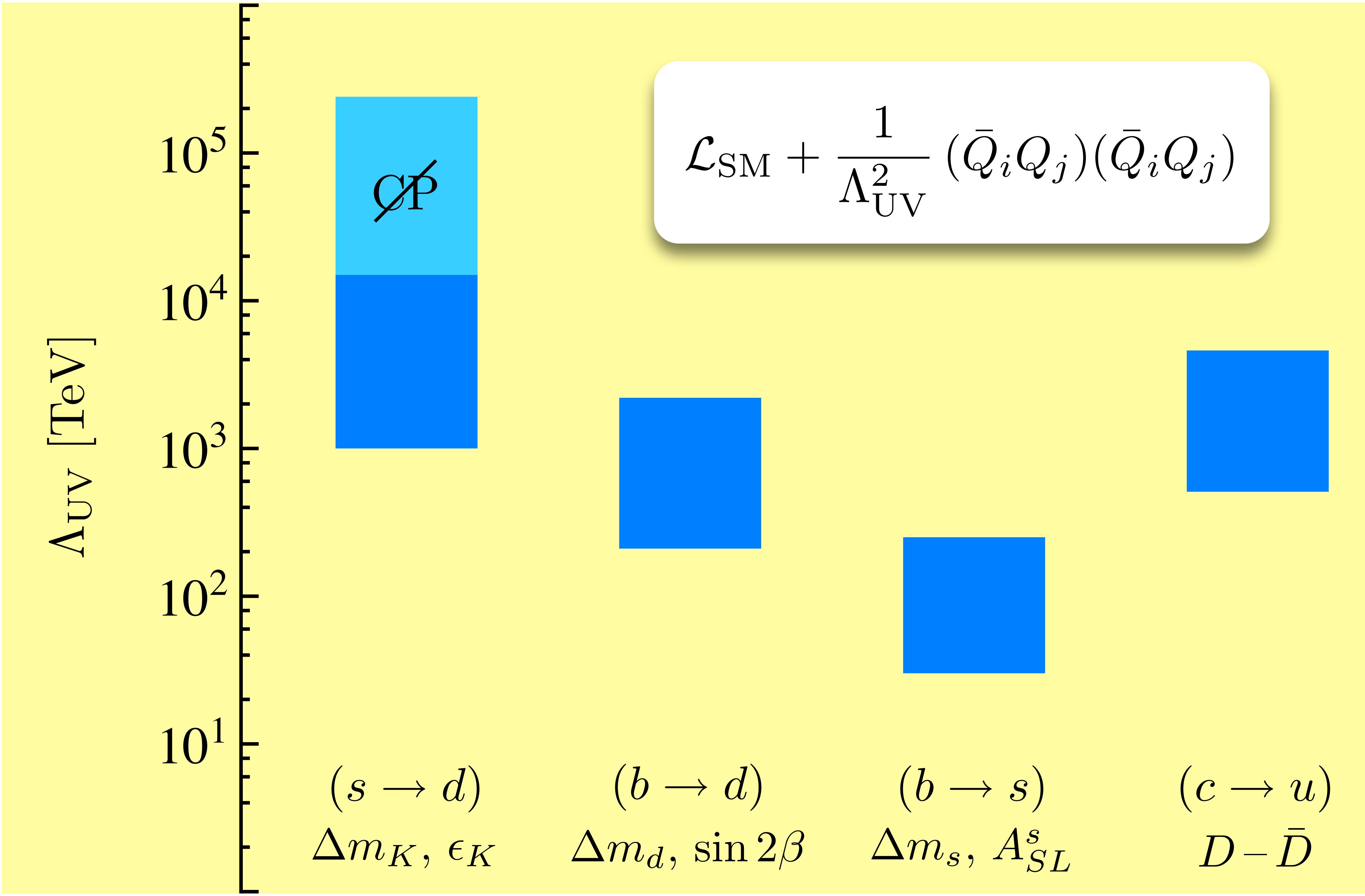
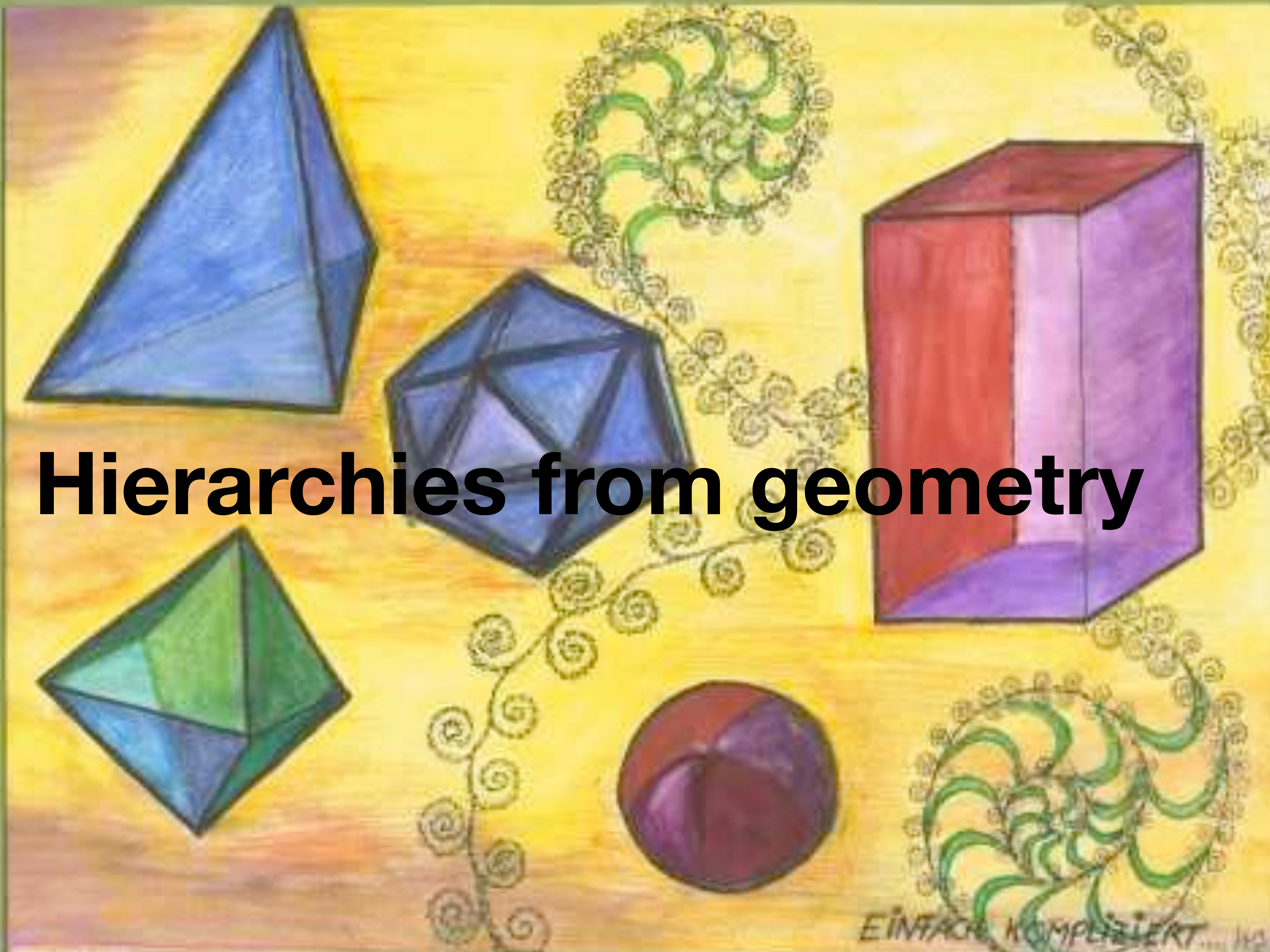
Flavor Structure in the SM and Beyond



Generic bounds without flavor symmetry

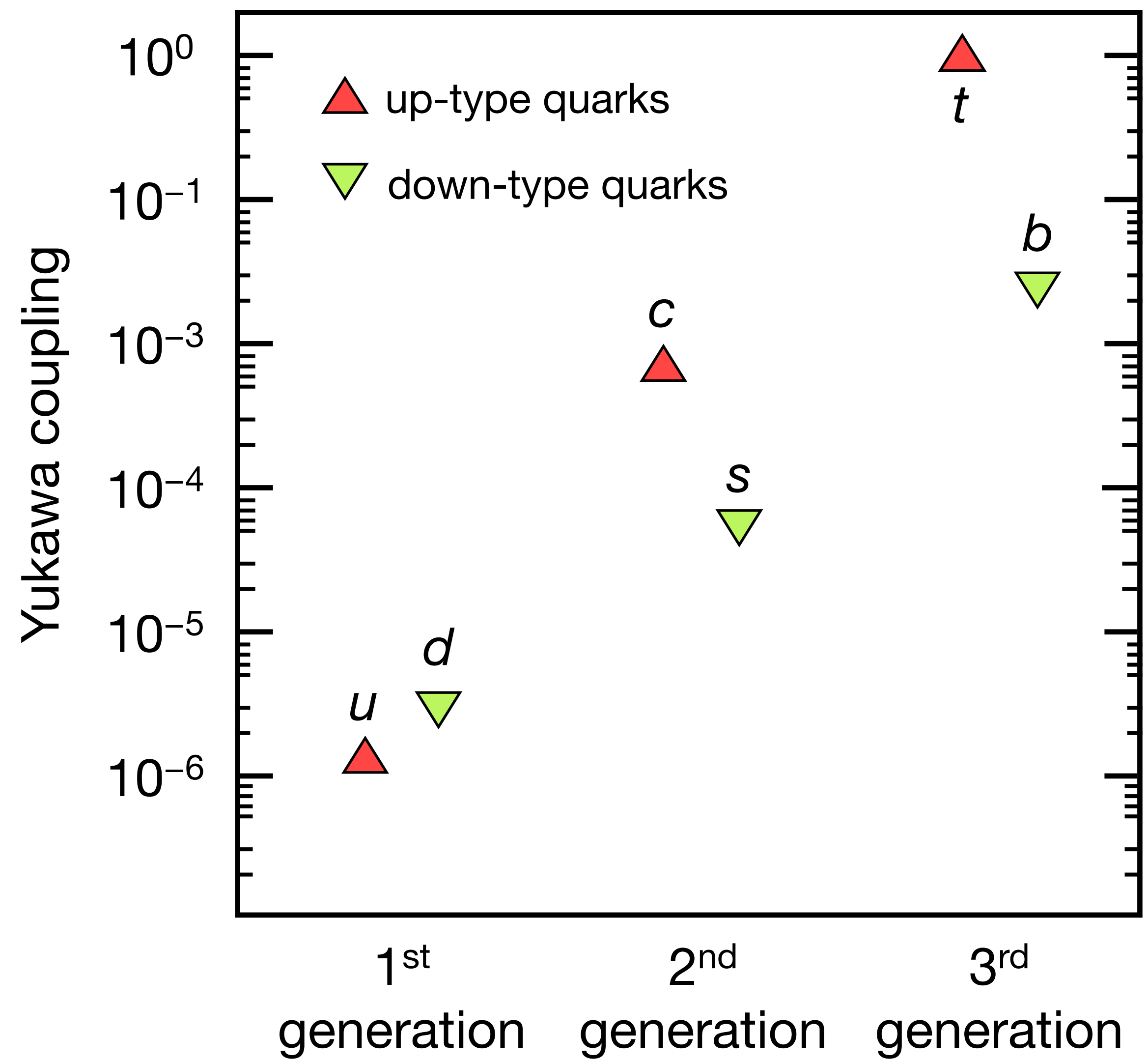
Hierarchies from geometry



What is the Dynamics of Flavor?

While SM describes flavor physics very accurately, it does not explain its mysteries:

- Why are there three generations in nature?
- Why does the spectrum of fermion masses cover many orders of magnitude (1st hierarchy)?



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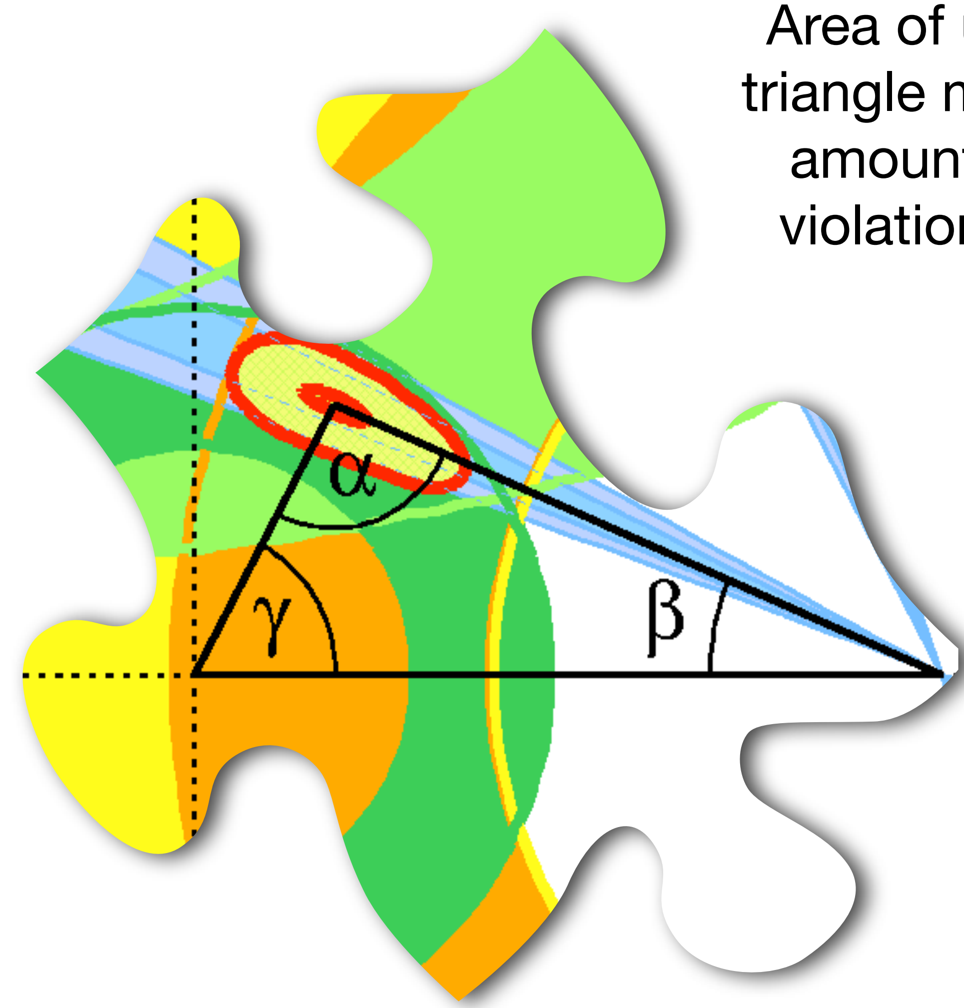
- Why are there three generations in nature?
- Why does the spectrum of fermion masses cover many orders of magnitude (1st hierarchy)?
- Why is the mixing between different generation governed by small mixing angles (2nd hierarchy)?
- Why is the CP-violating phase of the CKM matrix unsuppressed?

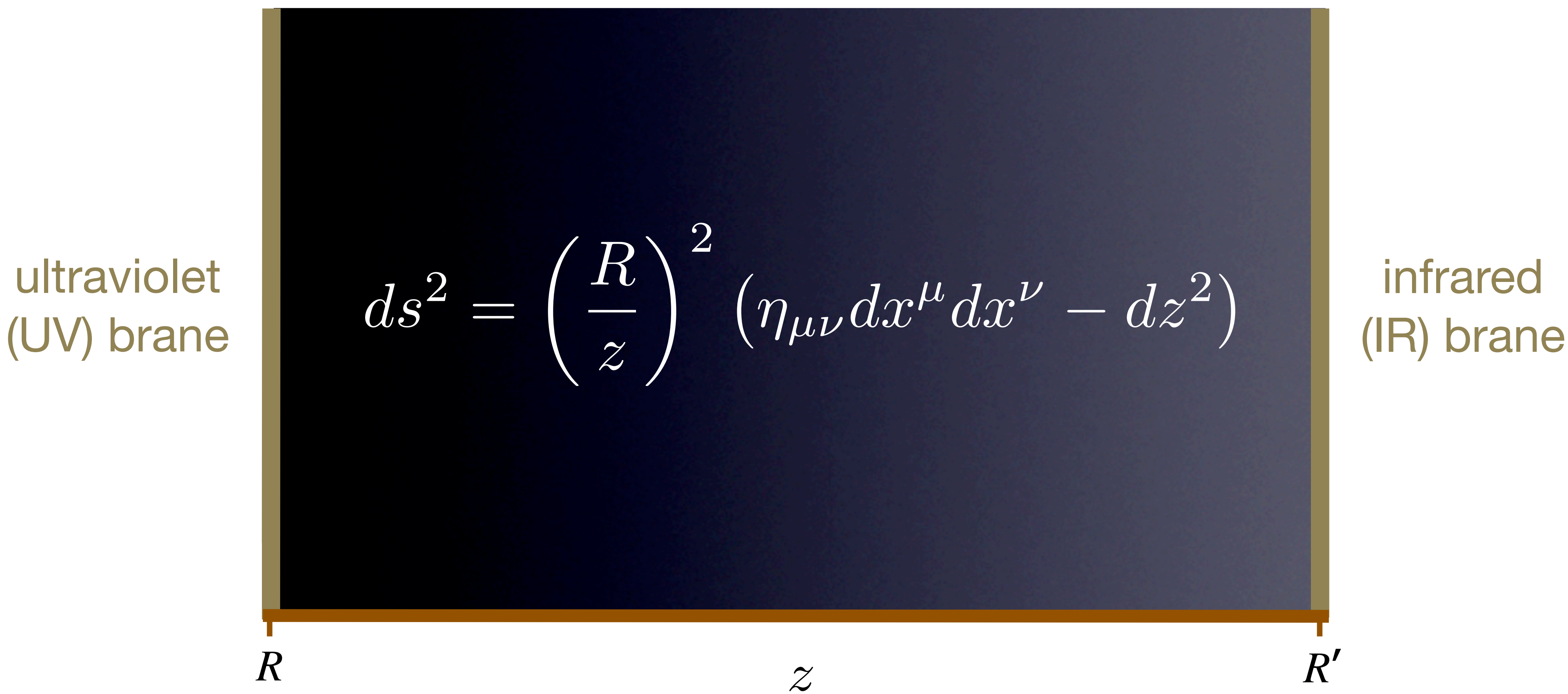


Area of unitarity triangle measures amount of CP violation in SM

Answers to these questions necessarily require going beyond the SM -- an interesting approach is offered by Randall-Sundrum models with warped extra dimensions

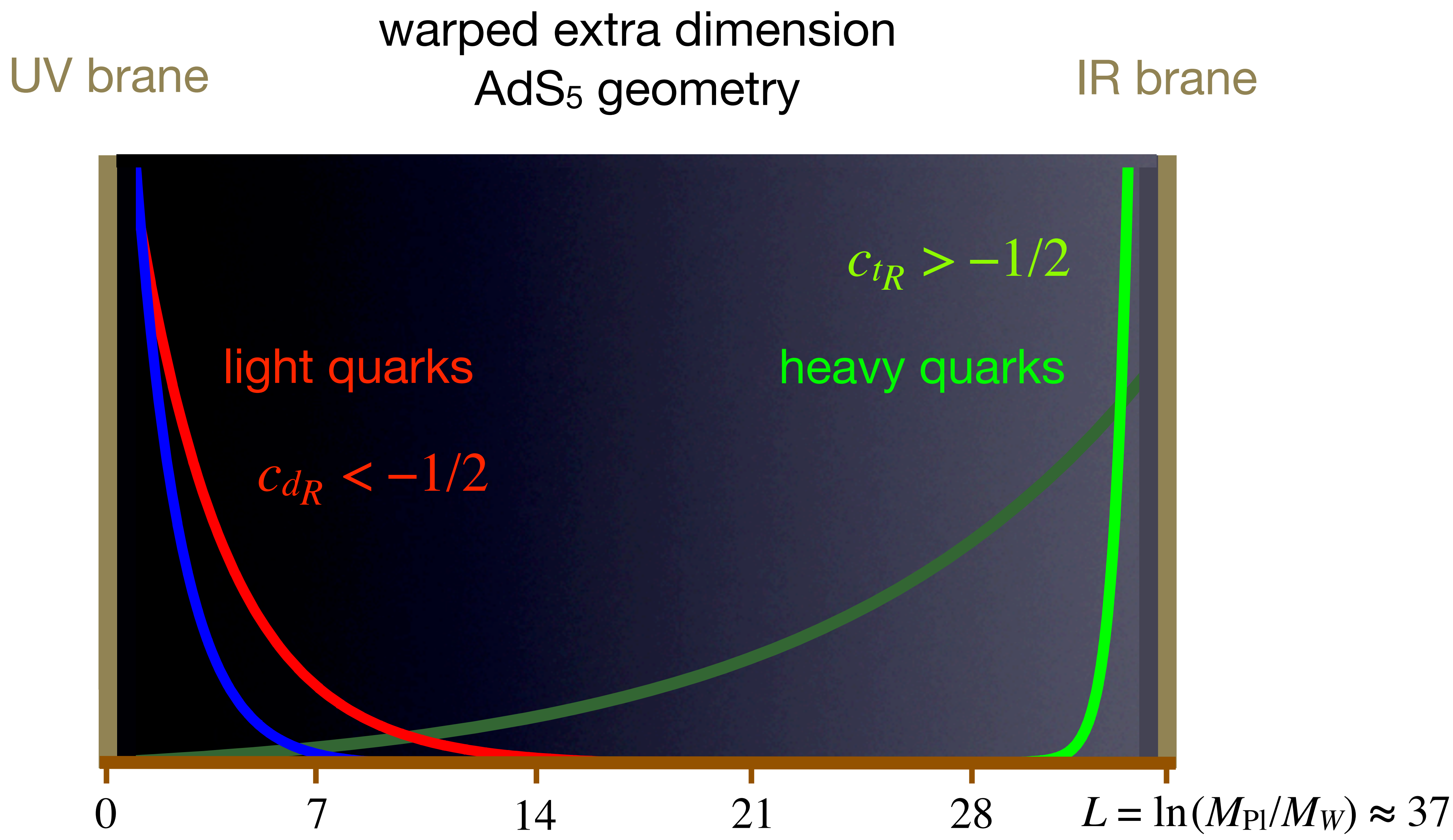
Flavor Structure in RS Models

Randall, Sundrum (1999)



- Solution to gauge hierarchy problem via gravitational redshift
- AdS/CFT calculable strong electroweak-symmetry breaking: holographic technicolor, composite Higgs
- Unification possible due to logarithmic running of couplings

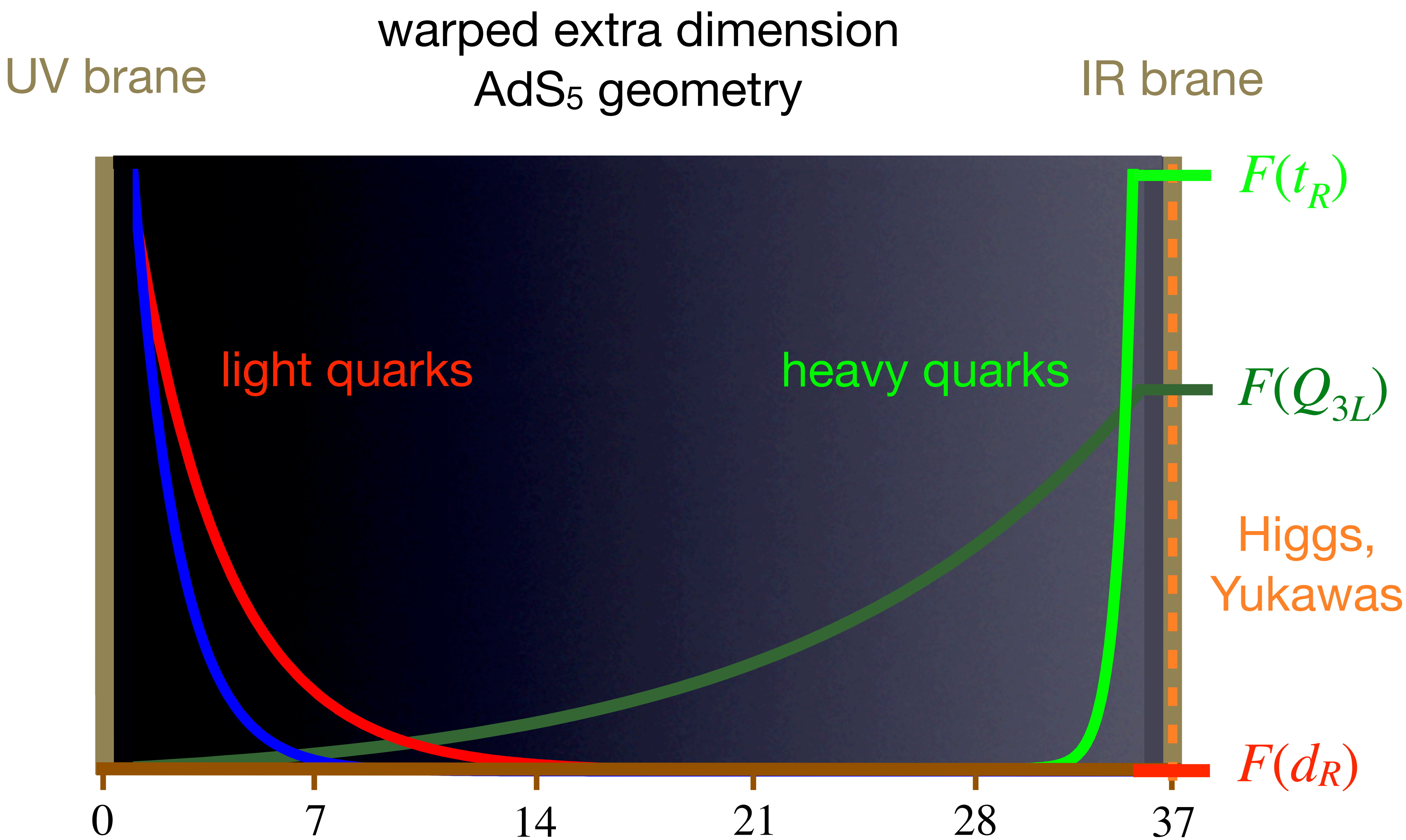
Flavor Structure in RS Models



Localization of fermions in extra dimension depends exponentially on O(1) parameters: five-dimensional bulk masses parameters c_q

Grossman, Neubert (1999); Ghergetta, Pomarol (2000)

Flavor Structure in RS Models



Overlaps $F(Q_L)$, $F(q_R)$ with IR-localized Higgs sector and Yukawa couplings are exponentially small for light quarks, while O(1) for top quark

Grossman, Neubert (1999); Ghergetta, Pomarol (2000)

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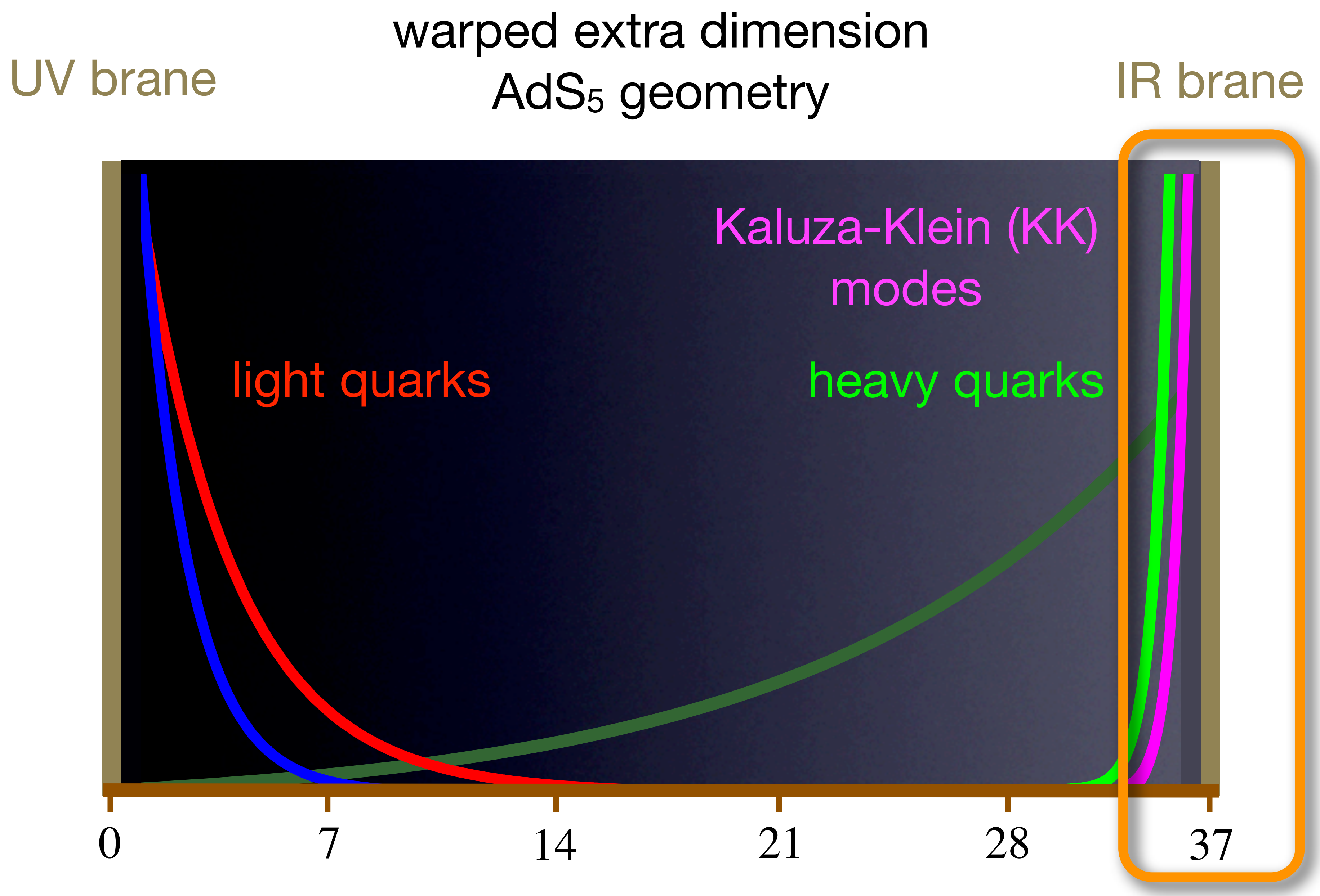

Kaluza-Klein (KK) excitations of SM particles live close to IR brane

Davoudiasl, Hewett, Rizzo (1999); Pomarol (1999)

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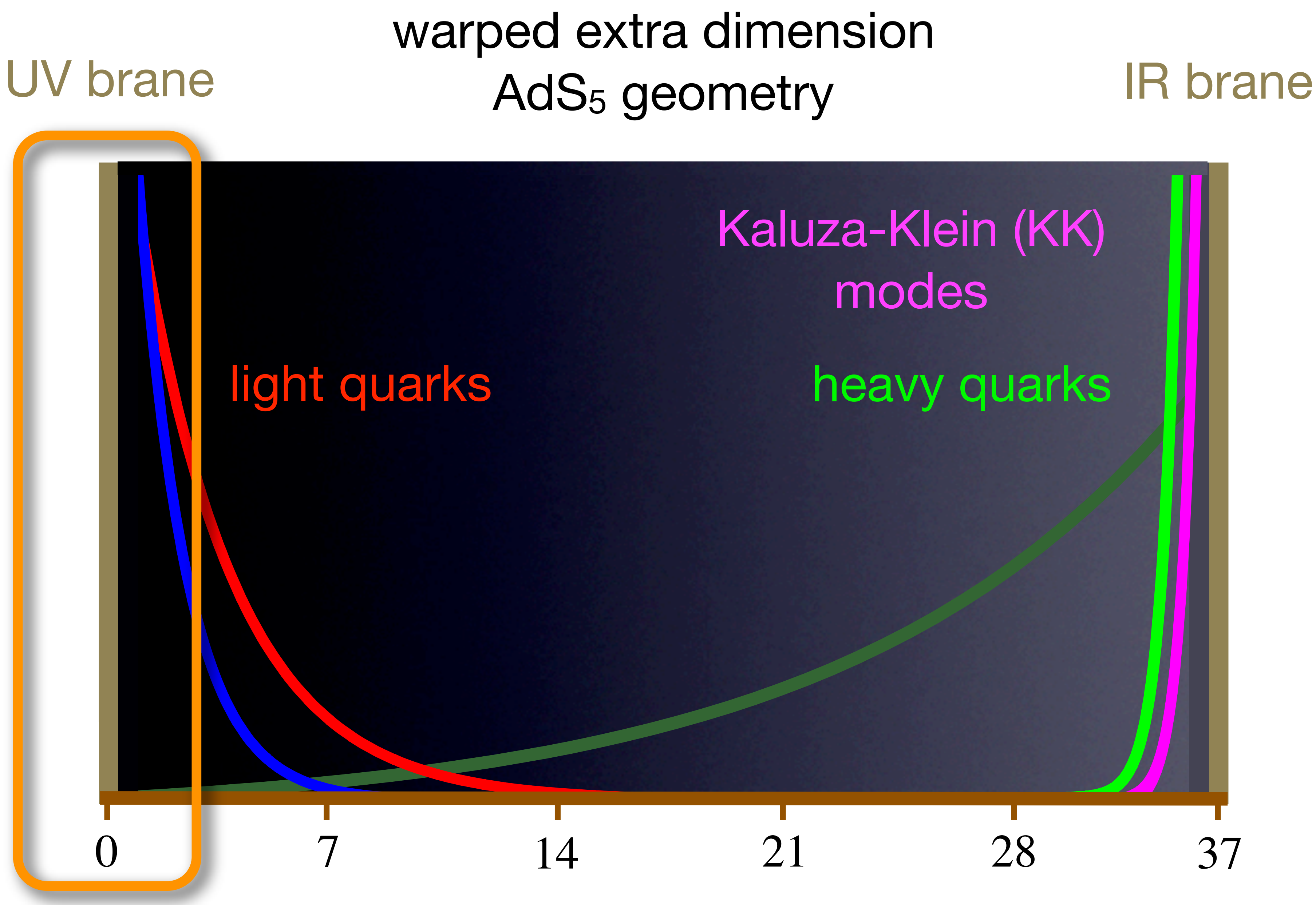
Flavor Structure in RS Models

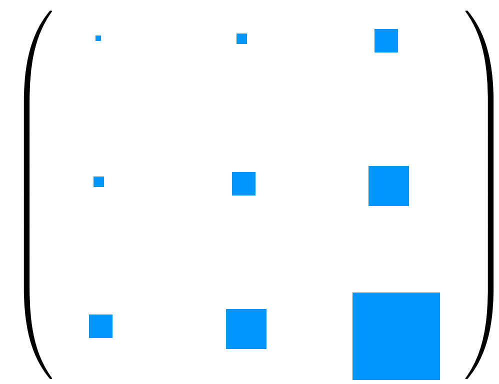


Since light quarks live in UV, their couplings to W and Z bosons, as well as to KK gauge bosons, are almost flavor-independent Gherghetta, Pomarol (2000)

Hierarchies of Quark Masses and CKM Angles

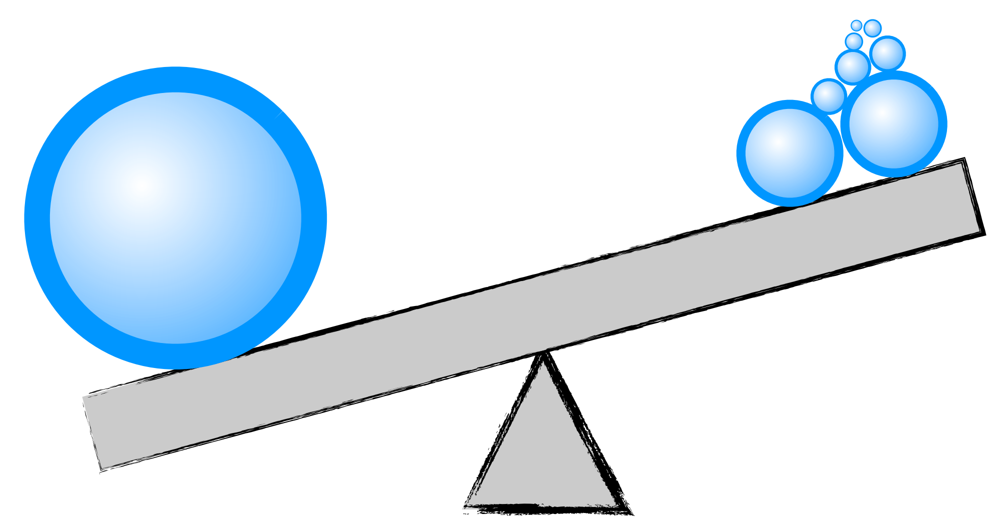
- SM mass matrices can be written as Huber (2003)

$$\boldsymbol{m}_q^{\rm SM} = \frac{v}{\sqrt{2}} \,{\rm diag}\left[F(Q_i)\right] \boldsymbol{Y}_q \,{\rm diag}\left[F(q_i)\right] =$$



where $\boldsymbol{Y}_q$ with $q = u,d$ are structureless, complex Yukawa matrices with O(1) entries, and $F(Q_i) << F(Q_j)$, $F(q_i) << F(q_j)$ for $i < j$

- In analogy to seesaw mechanism for neutrinos, matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices



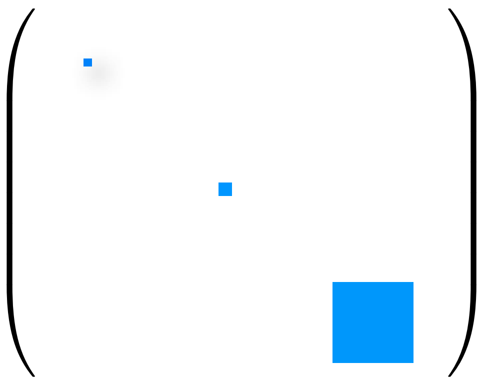
Warped-space Froggatt-Nielsen mechanism!

Froggatt, Nielsen (1979); Casagrande *et al*. (2008); Blanke *et al*. (2008)

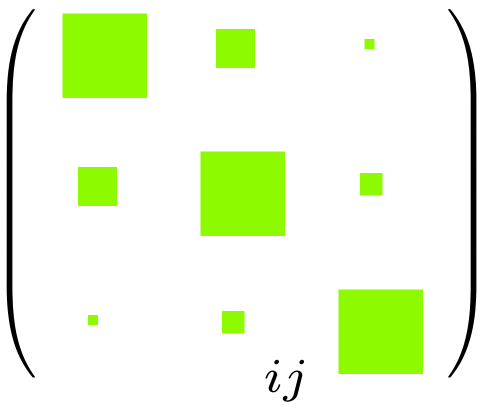
Hierarchies of Quark Masses and CKM Angles

- Thus:

$$\boldsymbol{m}_q \sim \frac{v}{\sqrt{2}}\,\mathrm{diag}\left[F(Q_i)F(q_i)\right] =$$

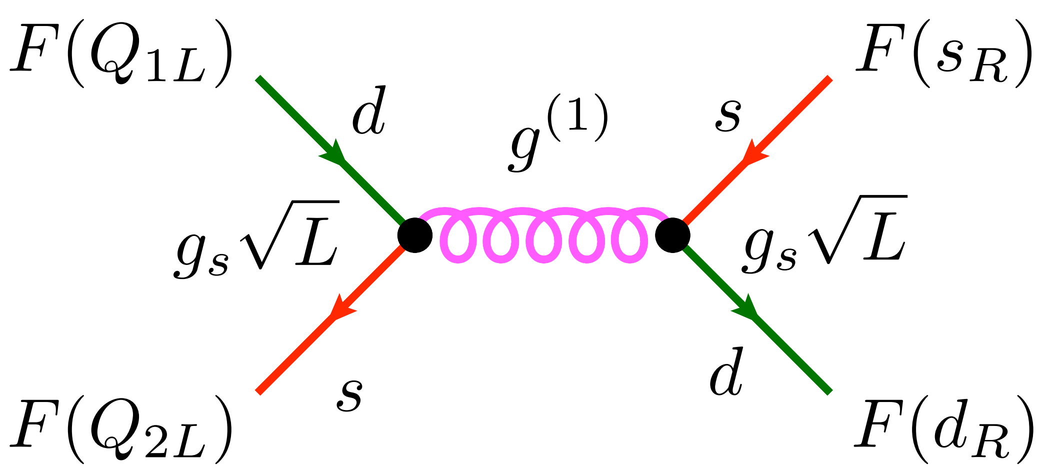


$$(V_{\mathrm{CKM}})_{ij} \sim \begin{cases} \dfrac{F(Q_i)}{F(Q_j)}, & i \le j \\[2ex] \dfrac{F(Q_j)}{F(Q_i)}, & i > j \end{cases} =$$



- Hierarchies predicted and readily adjusted by O(1) variations of bulk masses
- CP violating phase is predicted to be unsuppressed! Casagrande *et al*. (2008); Blanke *et al*. (2008)

RS-GIM Protection of FCNCs



$$\sim \frac{g_s^2}{M_{\rm KK}^2}\, L\, F(Q_{1L})F(d_R)\, F(Q_{2L})F(s_R)$$

- Quark FCNCs are induced at tree-level through virtual exchange of KK gauge bosons (including KK gluons!) Huber (2003); Burdman (2003); Agashe *et al*. (2004); Casagrande *et al*. (2008)
- Resulting FCNC couplings depend on same exponentially small overlaps $F(Q_L)$, $F(q_R)$ that generate fermion masses
- FCNCs involving quarks other than top are strongly suppressed! (true for all induced FCNC couplings) Agashe *et al*. (2004)

This mechanism suffices to suppress all but one of the dangerous FCNC couplings!

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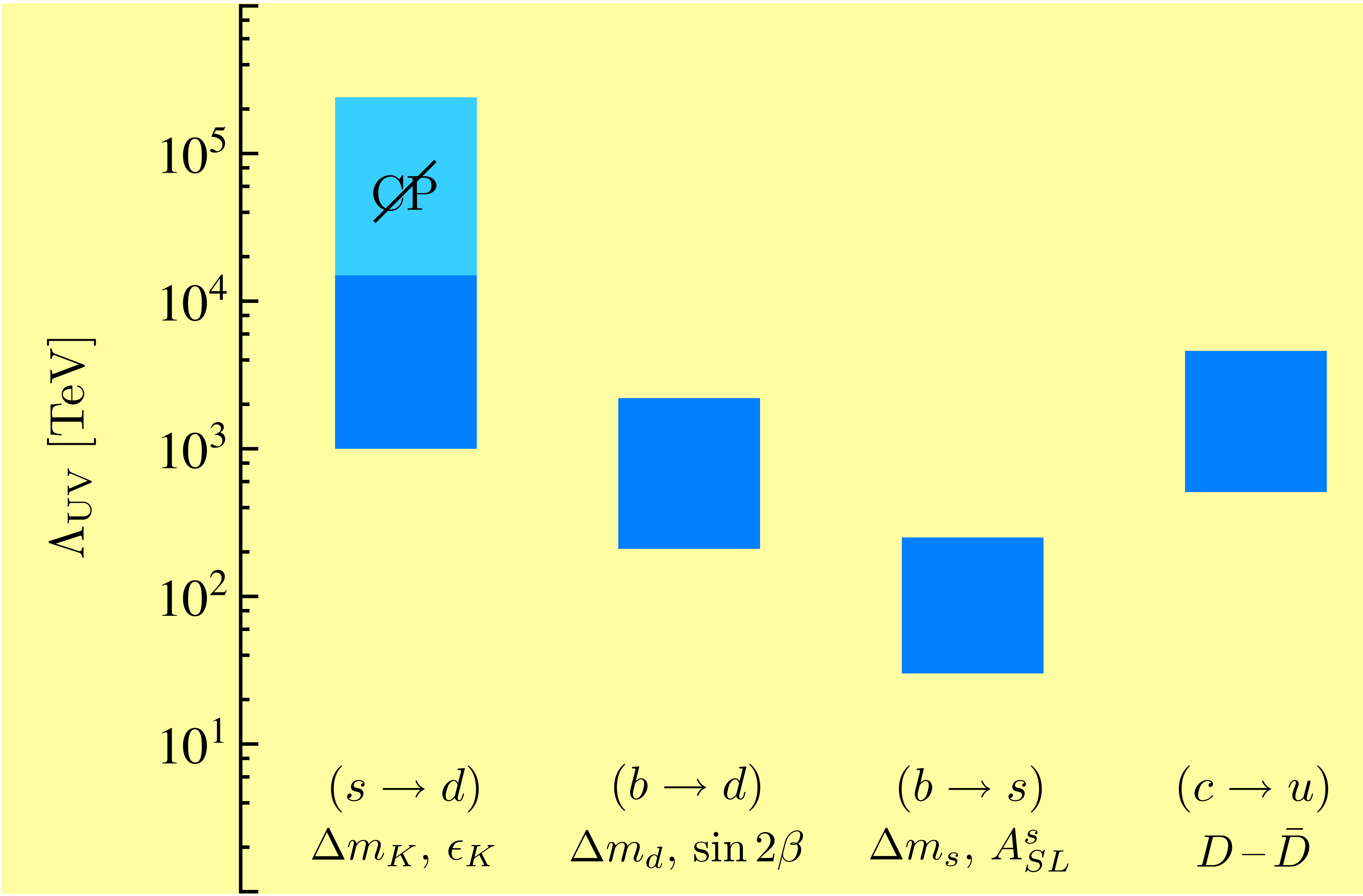
RS-GIM Protection of FCNCs



RS-GIM protection with KK masses of order few TeV

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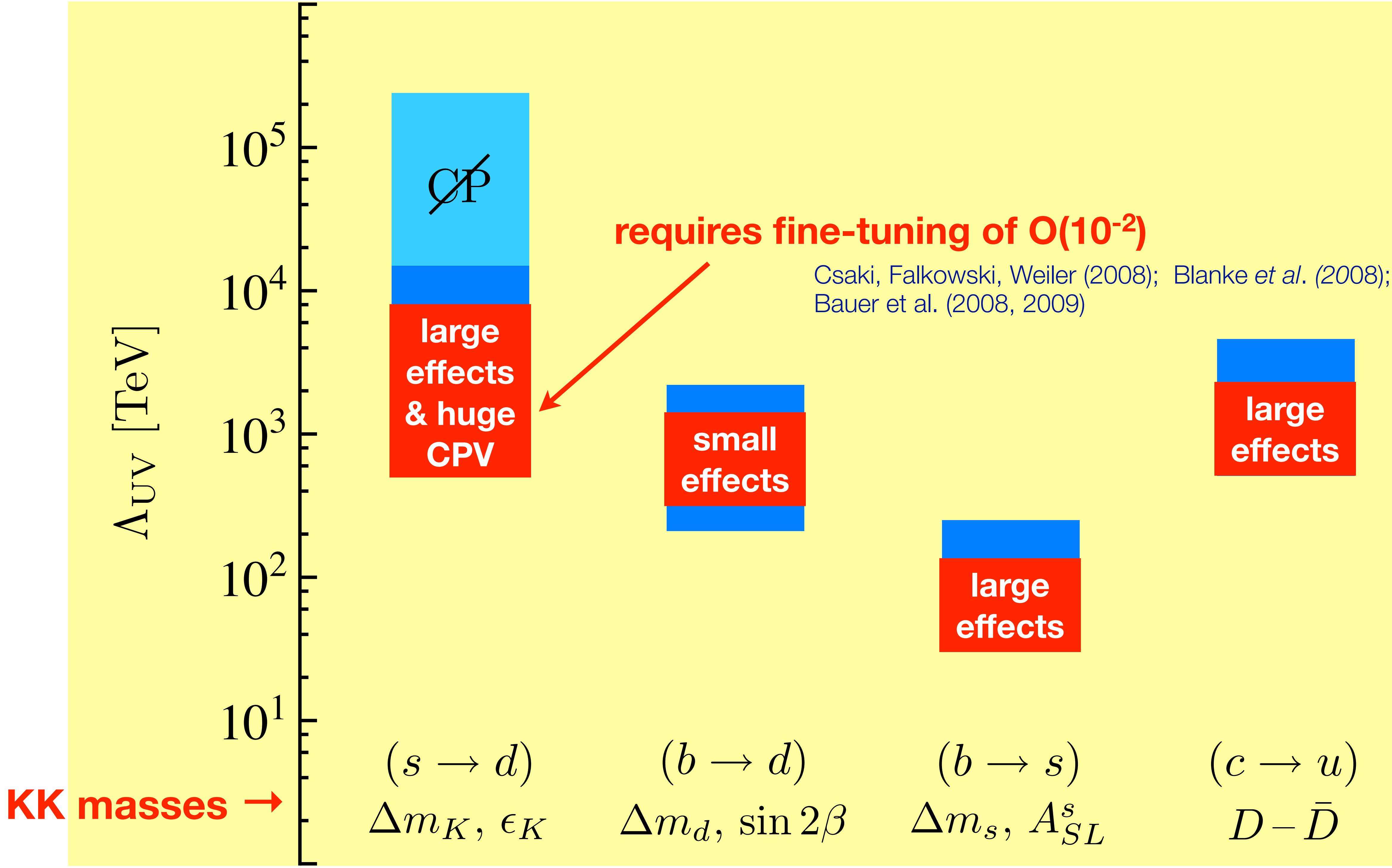
RS-GIM Protection of FCNCs



RS-GIM protection with KK masses of order few TeV

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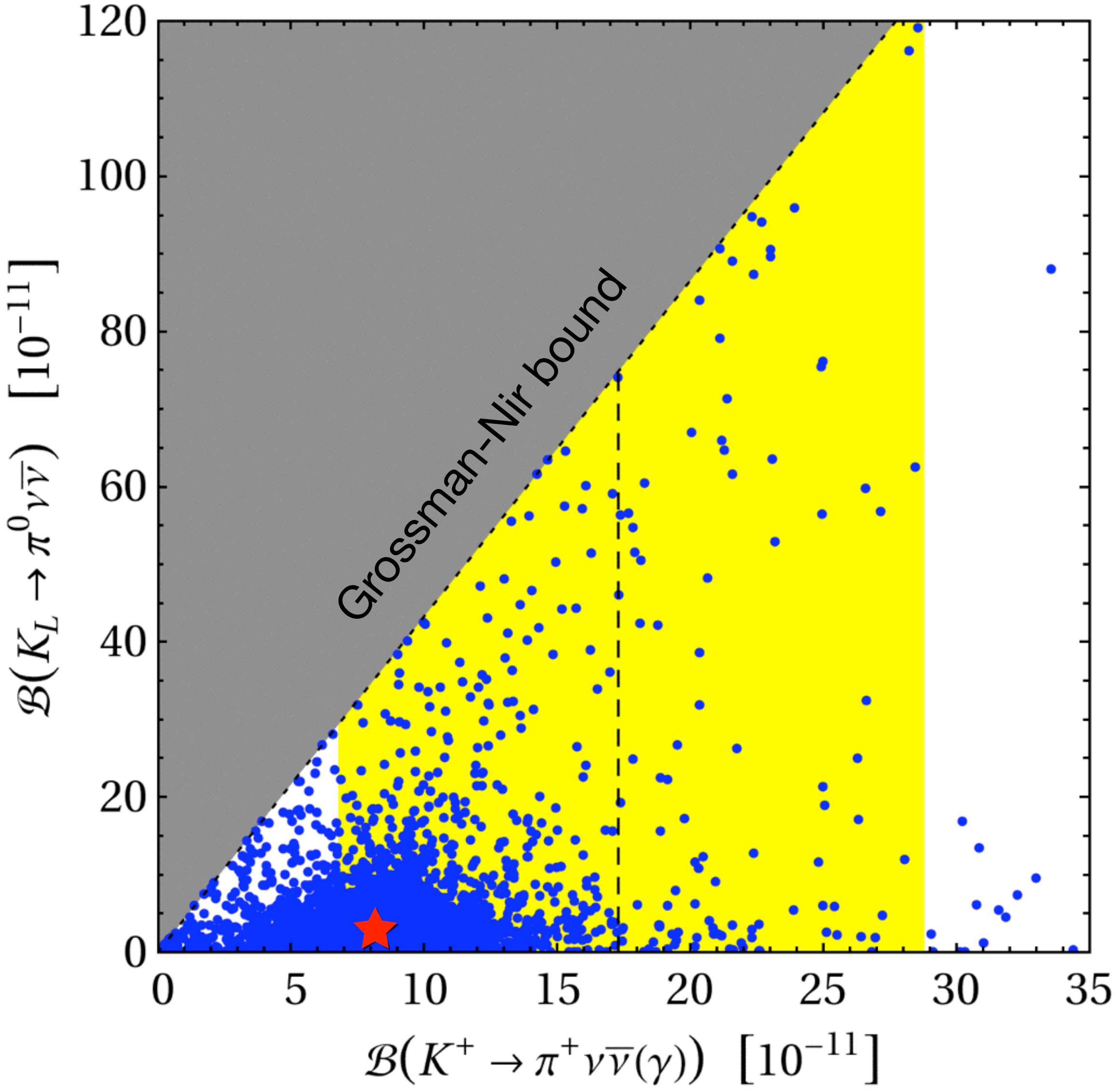
Golden Modes: Rare Kaon Decays

- Spectacular corrections are possible in very clean $K \to \pi\nu\bar{\nu}$ decays, even saturating the Grossman-Nir bound, $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 4.4\,\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$

Blanke *et al*. (2008); Bauer et al. (2009)



SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \approx 8.3 \cdot 10^{-11}$,

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$

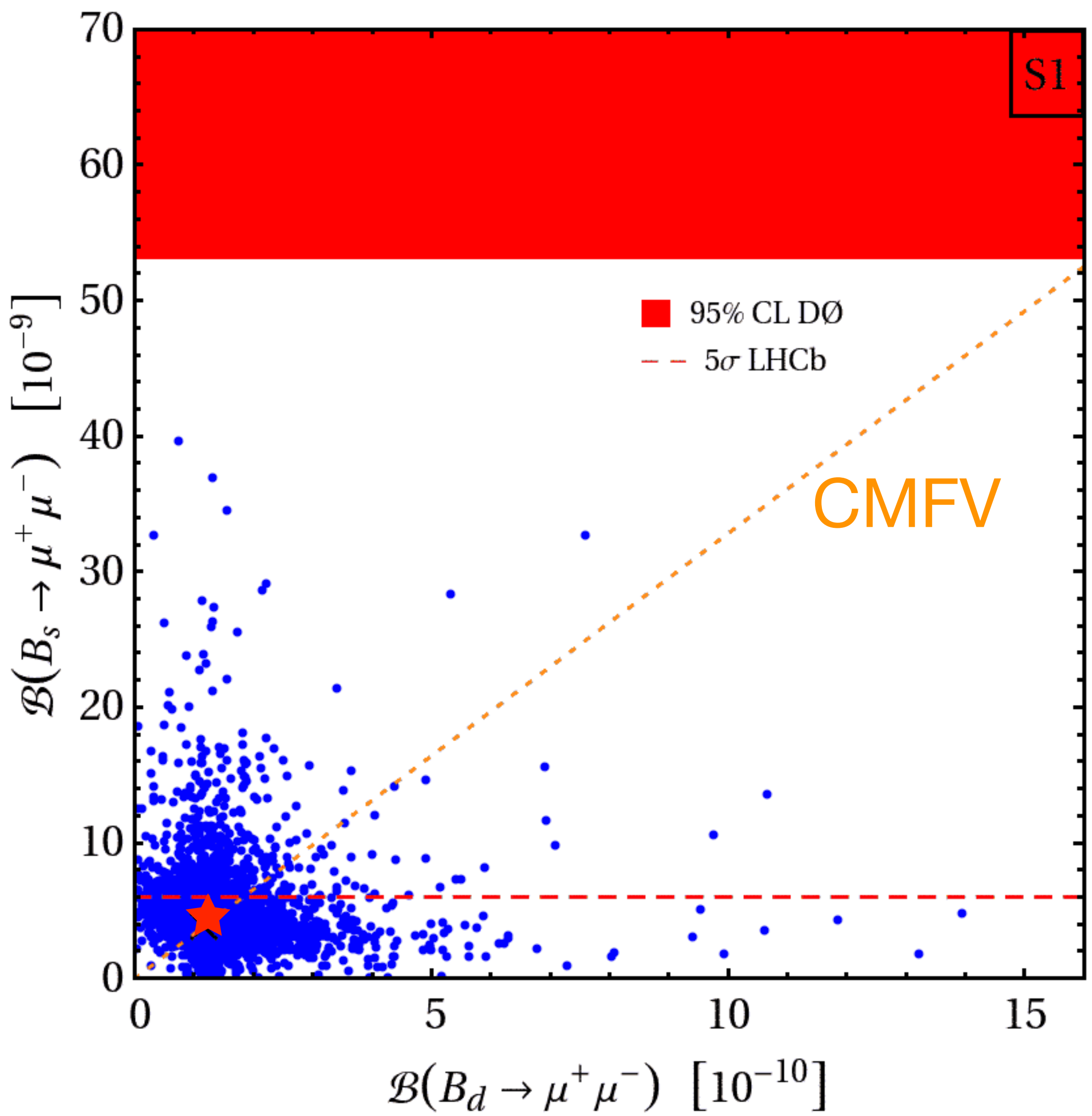
central value and 68% CL limit $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ from E949

consistent with quark masses, CKM parameters, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

Golden Modes: Rare B Decays

- Factor ~10 enhancements possible in rare $B_{d,s} \to \mu^+\mu^-$ modes without violation of $Z \to b\bar{b}$ constraints; effects largely uncorrelated with $|\varepsilon_K|$

Blanke *et al*. (2008); Bauer et al. (2009)



- ★ SM: $\mathcal{B}(B_d \to \mu^+\mu^-) \approx 1.2 \cdot 10^{-10}$,
  $\mathcal{B}(B_s \to \mu^+\mu^-) \approx 3.9 \cdot 10^{-9}$
- minimum of $5.5 \cdot 10^{-9}$ for 5σ discovery by LHCb, $2\ \text{fb}^{-1}$
- 95% CL upper limit from CDF: $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$
- consistent with quark masses, CKM parameters, $Z \to b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

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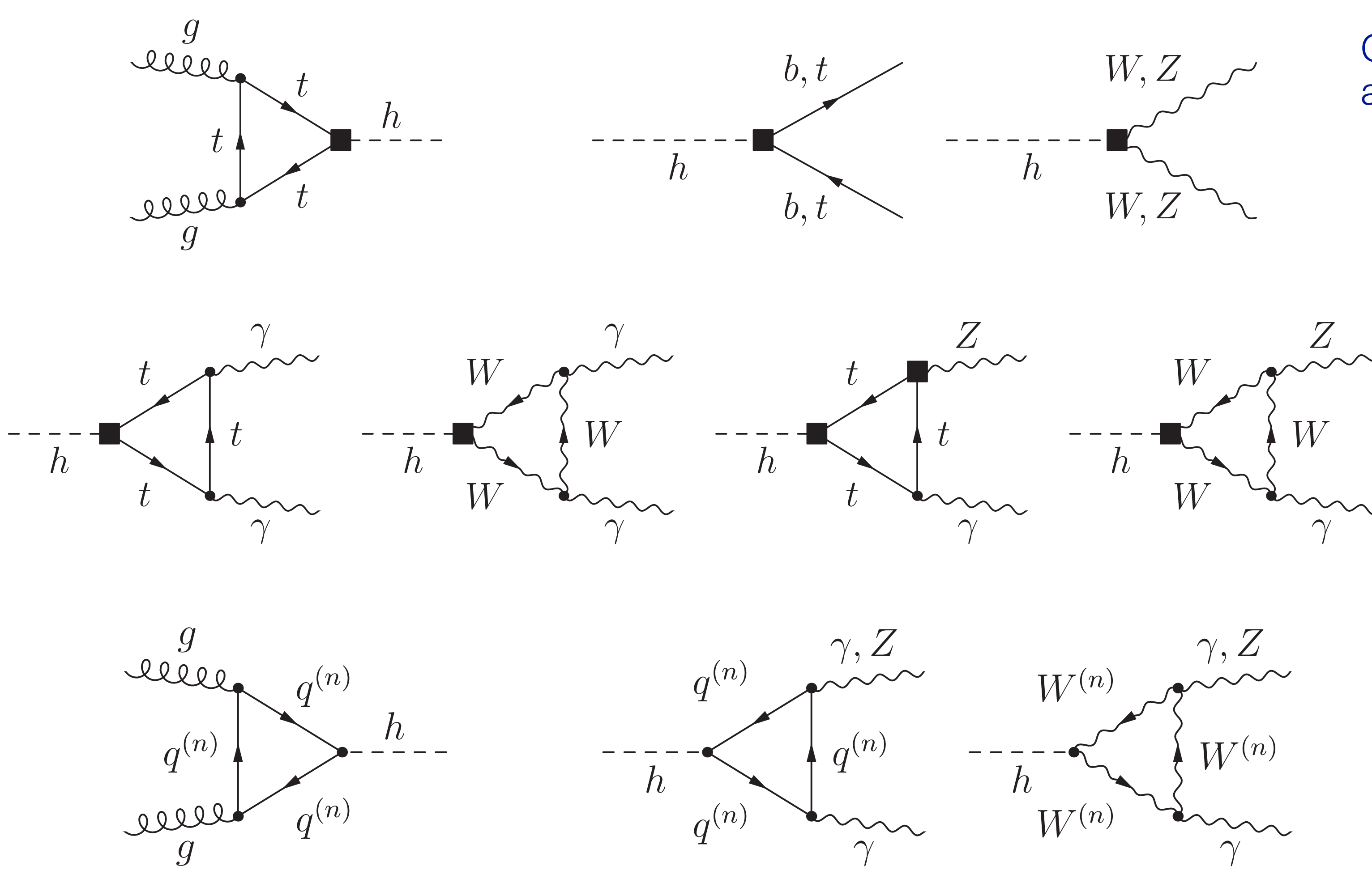
Correlations with Higgs physics

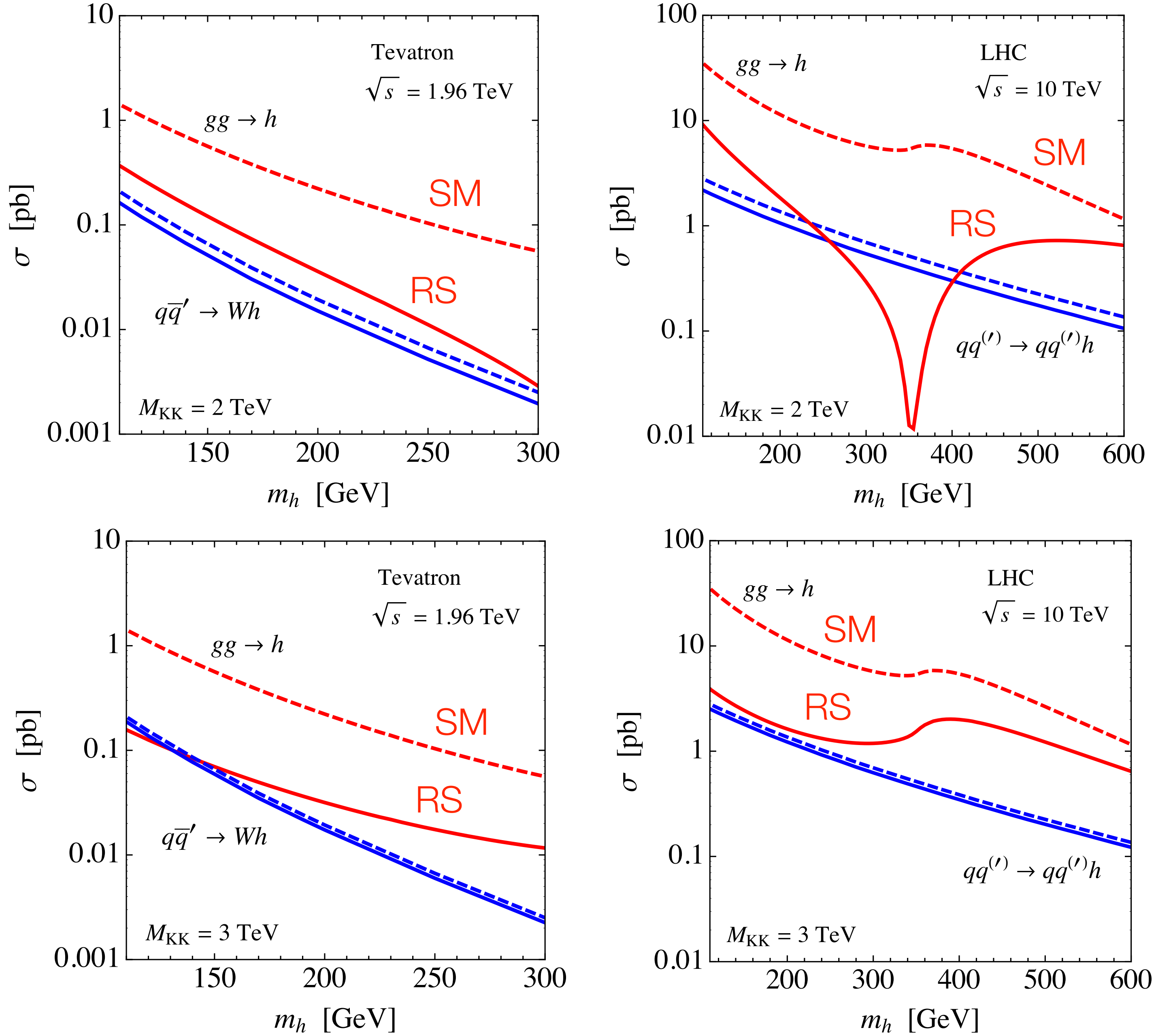
- Properties of the Higgs boson offer alternative ways to probe, via modifications of SM couplings and virtual effects from heavy KK states, the structure of warped extra-dimension models
- Recently, we have performed the first complete one-loop analysis of Higgs production and decays in the RS model with custodial symmetry



Casagrande, Goertz, Haisch, MN, Pfoh: arXiv:0510.4315

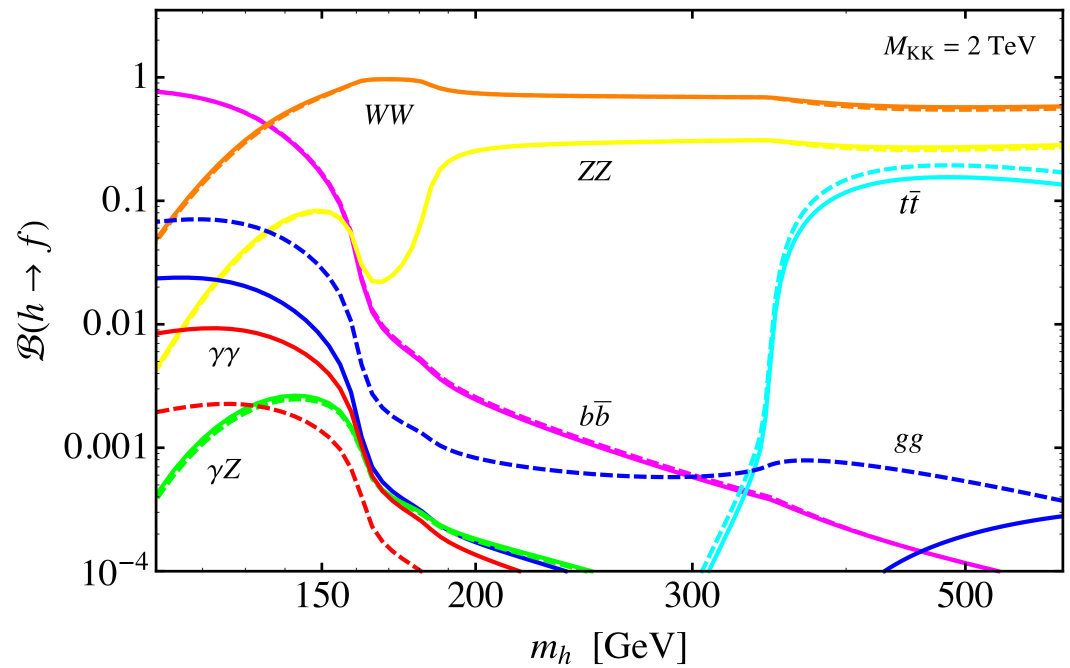
Higgs production cross sections

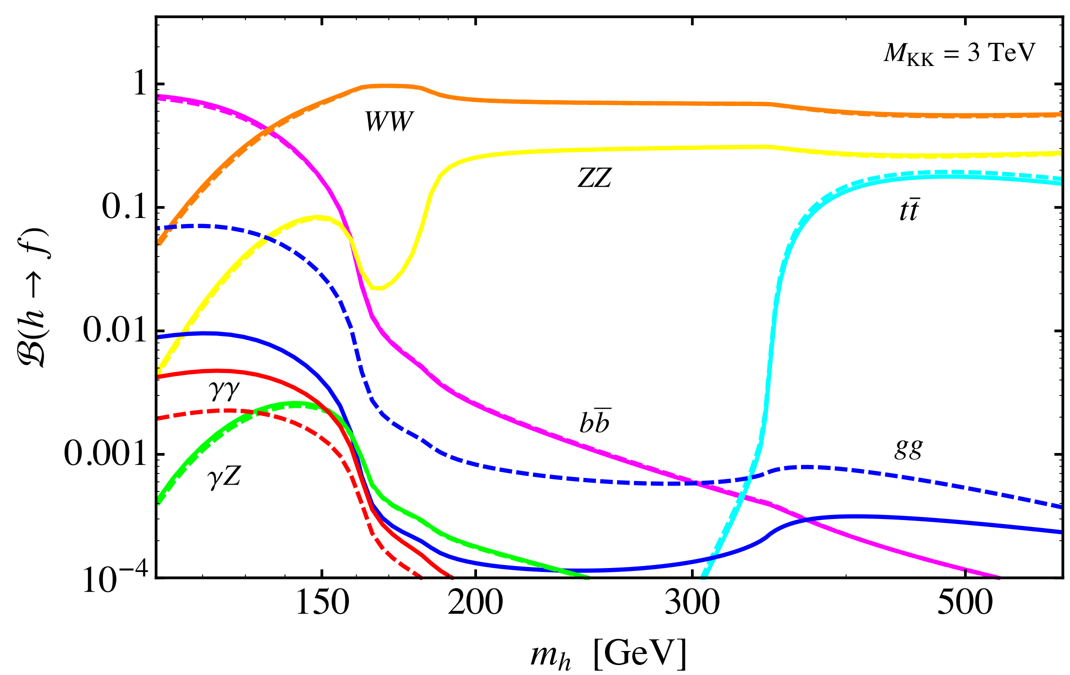
- Find possibly spectacular effects on Higgs production via gluon fusion, even for high KK masses ($m_{G^{(1)}_{\mathrm{KK}}} \approx 2.45 M_{\mathrm{KK}}$):



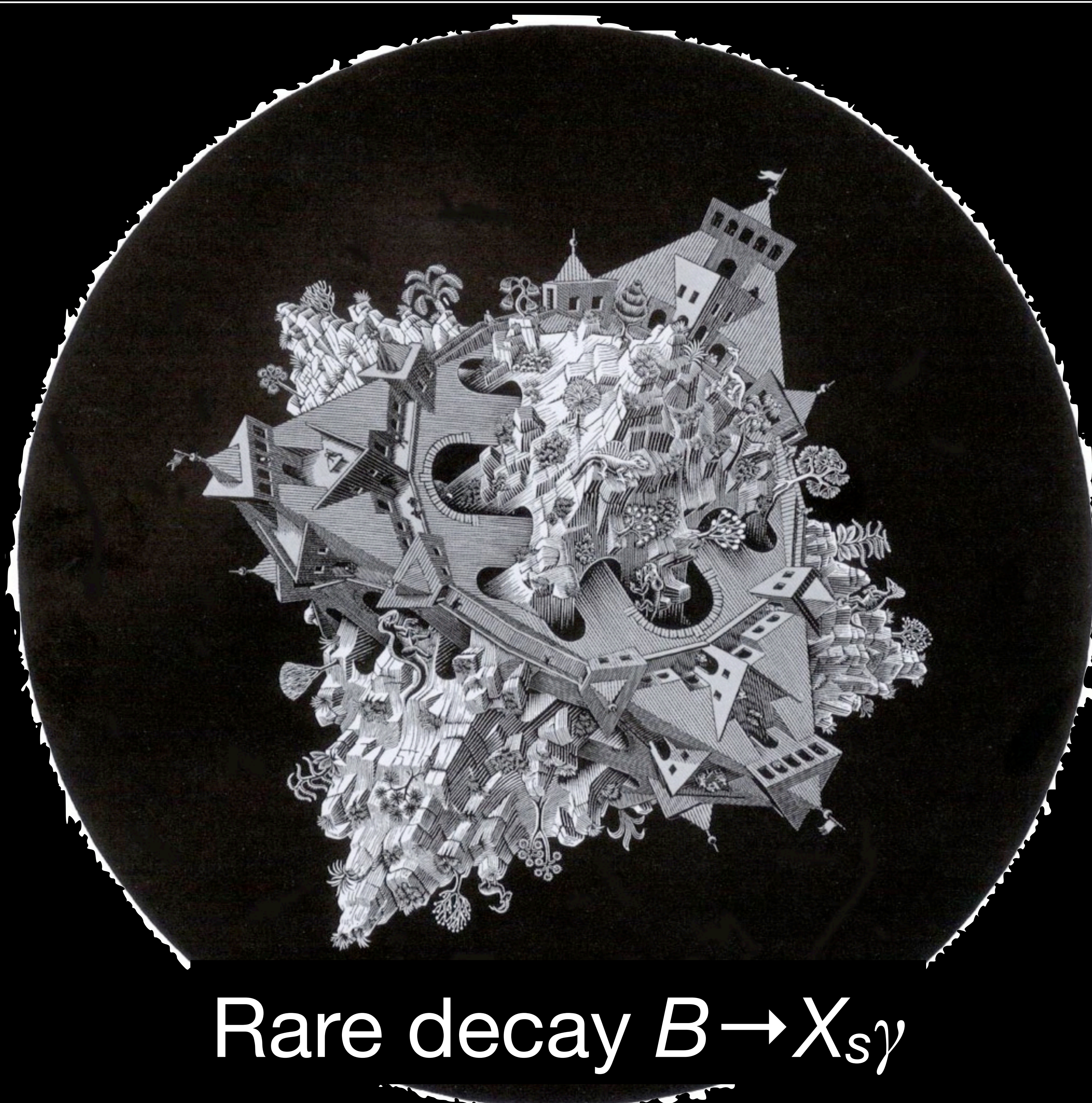
Higgs decay branching fractions

- Correspondingly, find possibly significant impact on $h \to gg$ and $h \to \gamma\gamma$ branching ratios:





Complementarity of High Energy and Precision



Rare decay $B \to X_s \gamma$

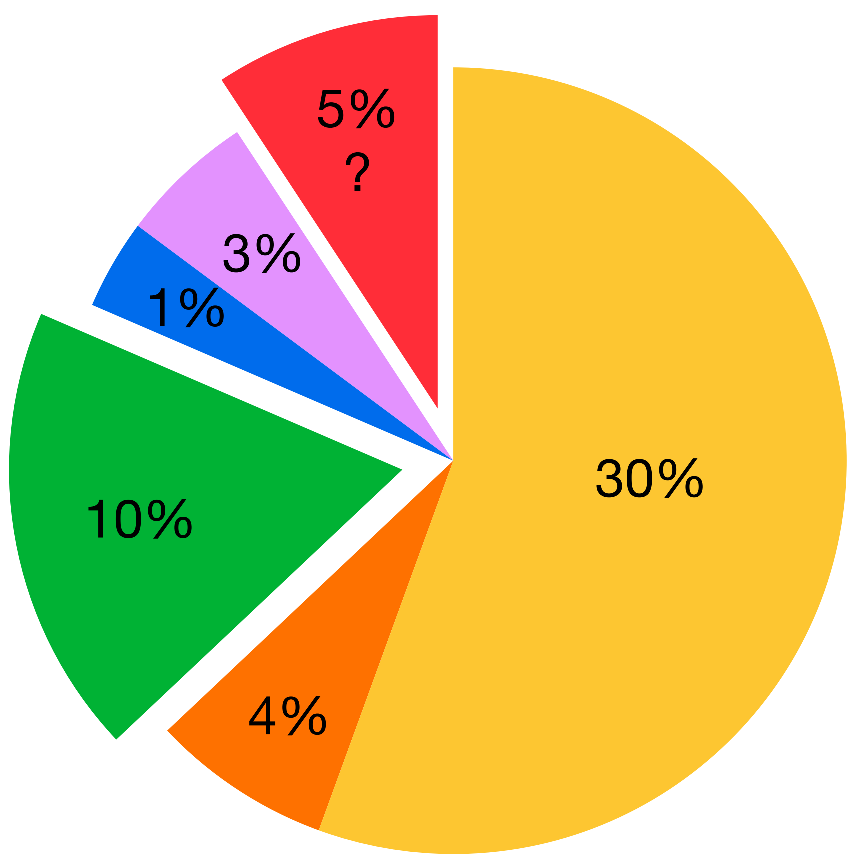
Probing FCNCs in $B\to X_s\gamma$ Decay

$$\mathcal{B}(B\to X_s\gamma)^{E_\gamma>1.6\ \mathrm{GeV}}_{\mathrm{SM}} = \mathcal{B}(B\to X_c e\bar{\nu})_{\mathrm{exp}}\left[\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\bar{\nu})}\right]_{\mathrm{LO}}$$

$$\times\left\{1+\mathcal{O}(\alpha_s)+\mathcal{O}(\alpha)+\mathcal{O}(\alpha_s^2)+\mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{m_b^2}\right)+\mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{m_c^2}\right)+\mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)\right\}$$

Misiak *et al.* (2006); Becher, Neubert (2006)

Lee, Neubert, Paz (2006)



NLO QCD

NLO EW

NNLO QCD

LO QCD + local $1/m_b^2$

LO QCD + local $1/m_c^2$

non-local (!) $1/m_b$

perturbative

non-perturbative

relative size of corrections compared to leading-order (LO) branching ratio

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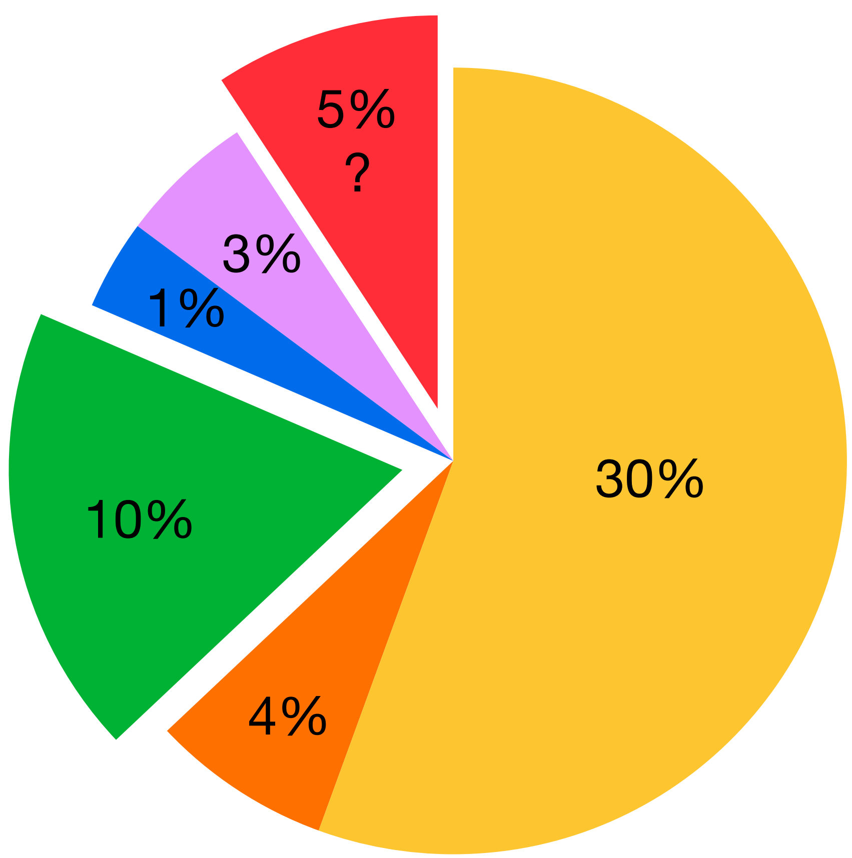
Probing FCNCs in $B \to X_s \gamma$ Decay

$$\mathcal{B}(B \to X_s \gamma)_{\rm SM}^{E_\gamma > 1.6\ \rm GeV} = \mathcal{B}(B \to X_c e \bar{\nu})_{\rm exp} \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to c e \bar{\nu})} \right]_{\rm LO}$$

$$\times \left\{ 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{m_b^2} \right) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{m_c^2} \right) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b} \right) \right\}$$

Misiak *et al.* (2006); Becher, Neubert (2006)

Lee, Neubert, Paz (2006)



NNLO perturbative calculation (technically difficult) and systematic estimate of **non-local power corrections** (conceptually difficult) are required in order to obtain an uncertainty of 5%

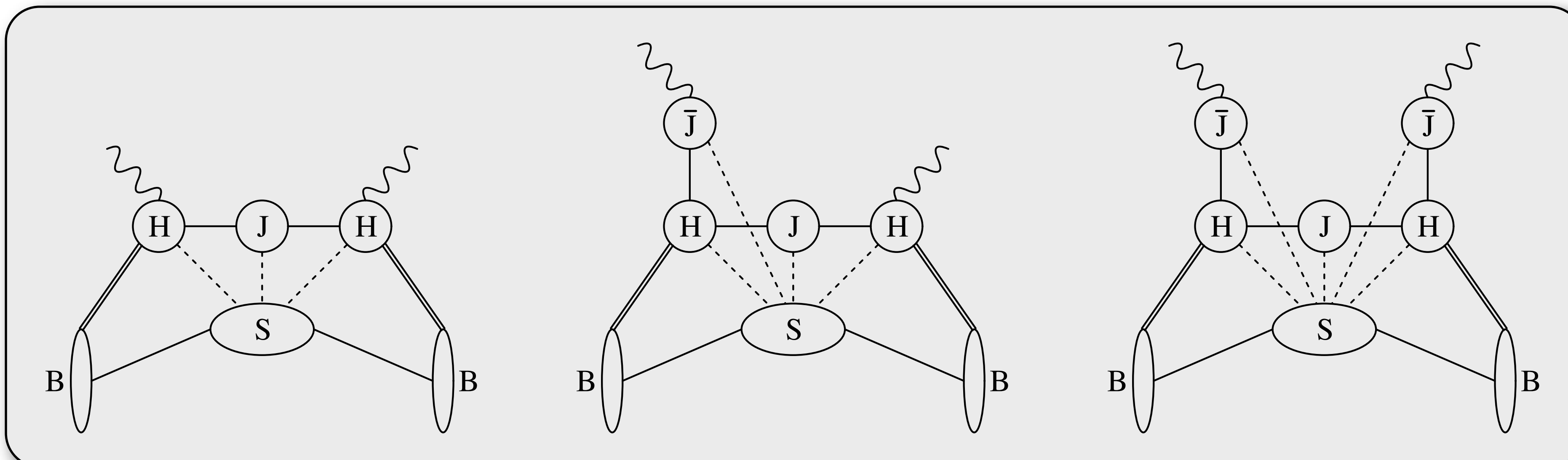
$$\mathcal{B}(B \to X_s \gamma)_{\rm NNLO}^{E_\gamma > 1.6\,\rm GeV} = (3.15 \pm 0.23) \times 10^{-4}$$

$$\mathcal{B}(B \to X_s \gamma)_{\rm exp}^{E_\gamma > 1.6\,\rm GeV} = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$$

relative size of corrections compared to leading-order (LO) branching ratio

Probing FCNCs in $B \to X_s\gamma$ Decay

Systematic analysis of non-local Λ_{QCD}/m_b corrections based on novel factorization theorem derived using soft-collinear effective theory:



Corrections to short-distance calculation of decay rate:

Benzke, Lee, Neubert, Paz: arXiv:1003.5012

$$\mathcal{F}_E(\Delta) = \frac{C_1(\mu)}{C_{7\gamma}(\mu)} \frac{\Lambda_{17}(m_c^2/m_b,\mu)}{m_b} + \frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)} 4\pi\alpha_s(\mu) \frac{\Lambda_{78}^{\rm spec}(\mu)}{m_b} + \left(\frac{C_{8g}(\mu)}{C_{7\gamma}(\mu)}\right)^2 \left[4\pi\alpha_s(\mu)\frac{\Lambda_{88}(\Delta,\mu)}{m_b} - \frac{C_F\alpha_s(\mu)}{9\pi}\frac{\Delta}{m_b}\ln\frac{\Delta}{m_s}\right] + \dots$$

Our estimate:

$$-5.1\% < \mathcal{F}_E(\Delta) < +4.2\%$$

Irreducible theoretical uncertainty!

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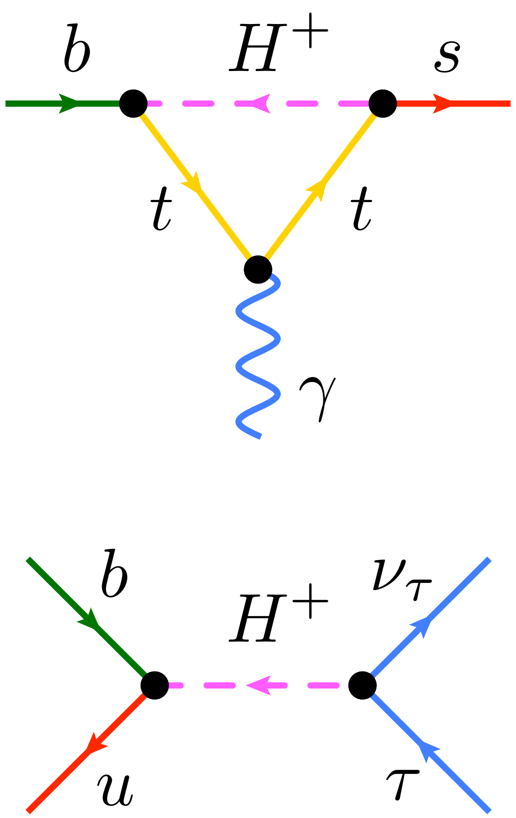
Impact on New Physics: Type-II 2HDM

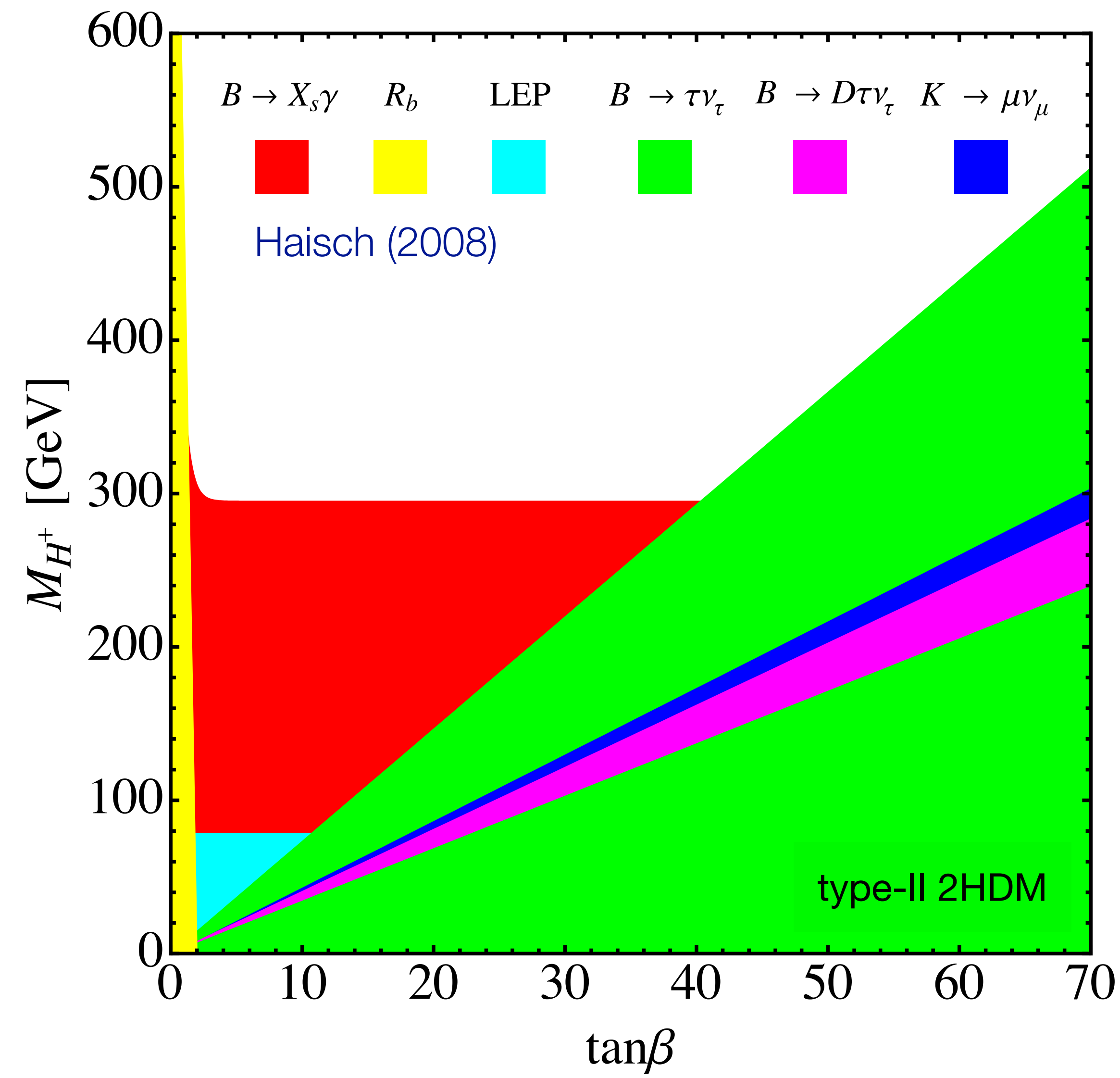


2HDM diagrams

$$\frac{m_t^2}{M_{H^+}^2} \ln \frac{m_t^2}{M_{H^+}^2}$$

$$\tan^2\beta \, \frac{m_B^2}{M_{H^+}^2}$$

M_{H^+} dependence of amplitude



Flavor physics, in particular $B \to X_s\gamma$ and $B \to \tau\nu$, yield constraints much stronger than those derived from LEP data

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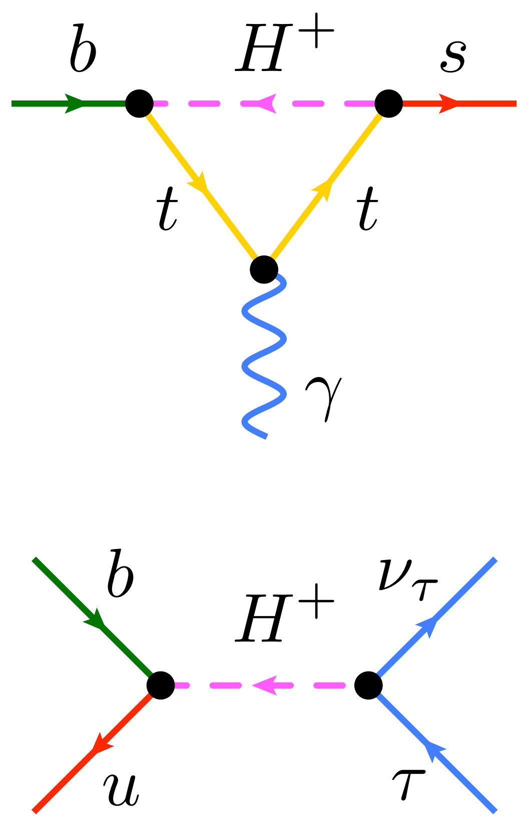
Impact on New Physics: Type-II 2HDM

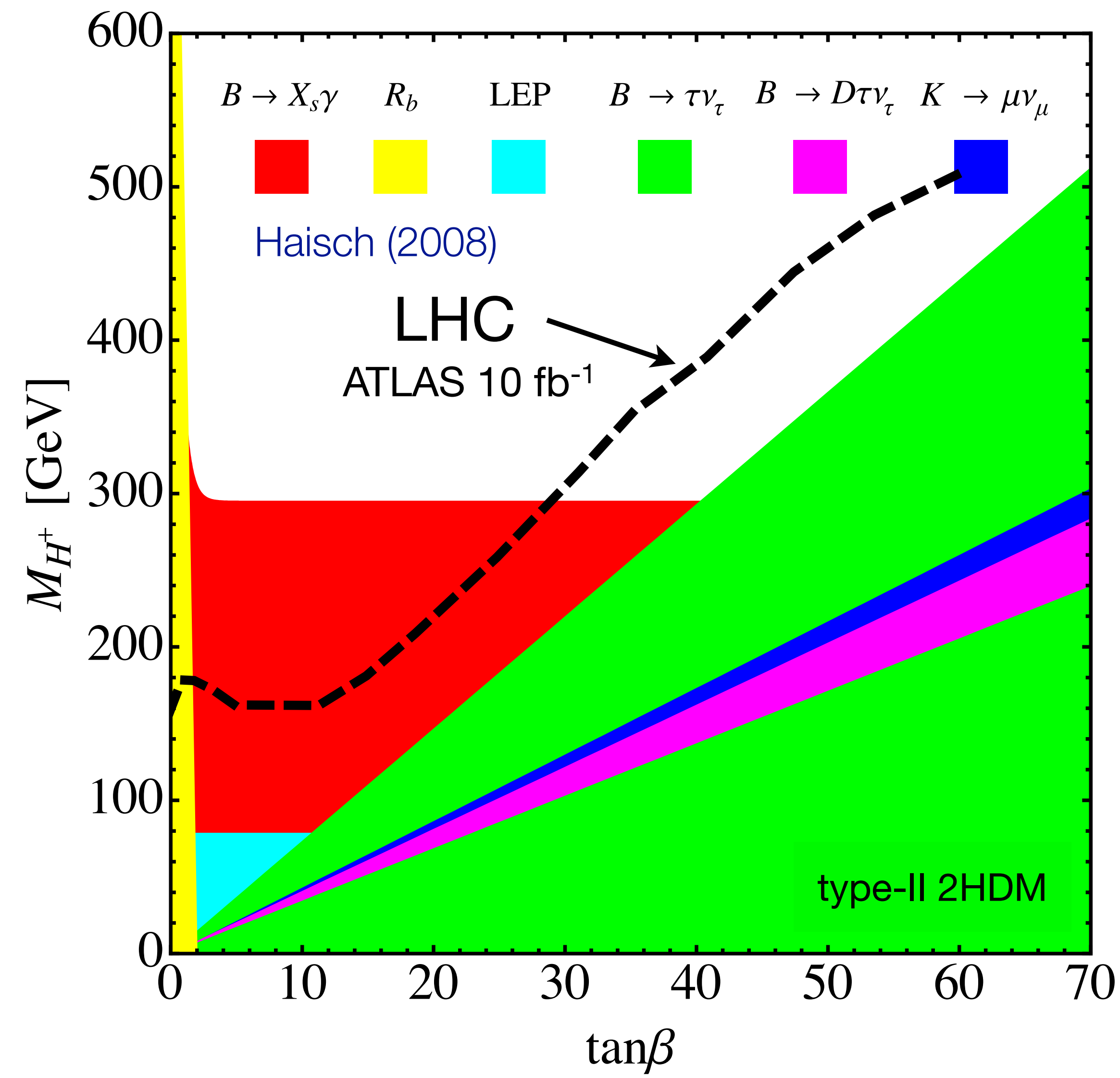


2HDM diagrams

$$\frac{m_t^2}{M_{H^+}^2} \ln \frac{m_t^2}{M_{H^+}^2}$$

$$\tan^2\beta \, \frac{m_B^2}{M_{H^+}^2}$$

M_{H^+} dependence of amplitude



Existing constraints in $\tan\beta$-M_{H^+} plane from flavor physics are comparable and complementary to the expected 95% CL exclusion limits from LHC, derived using $gg, gb \to t(b)H^+$ followed by $H^+ \to \tau\nu_\tau, tb$

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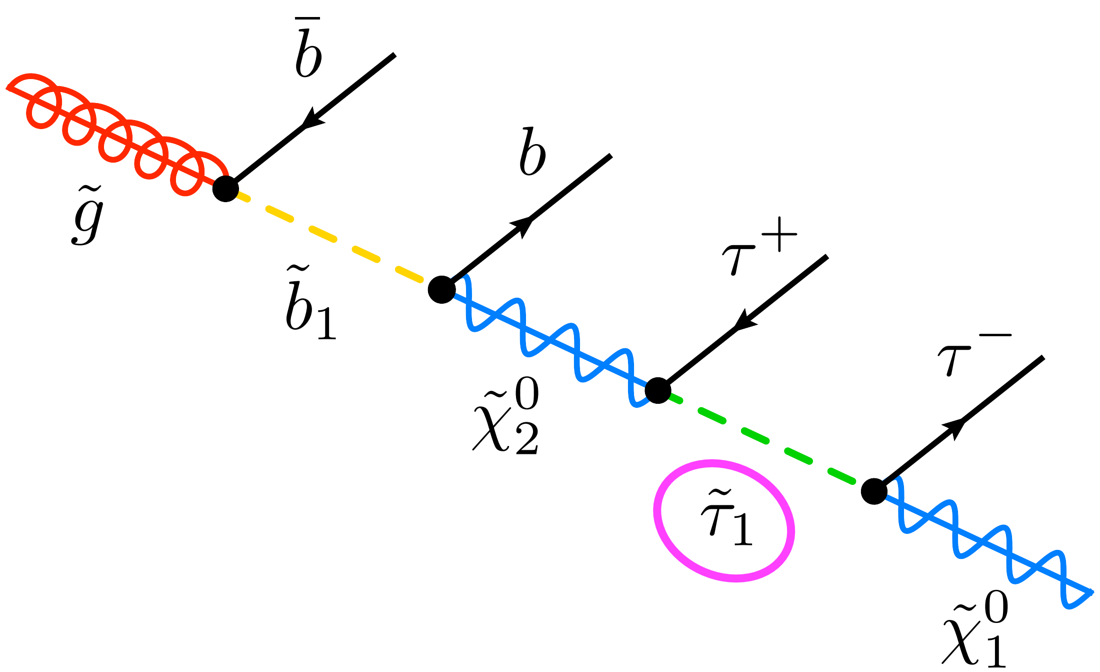
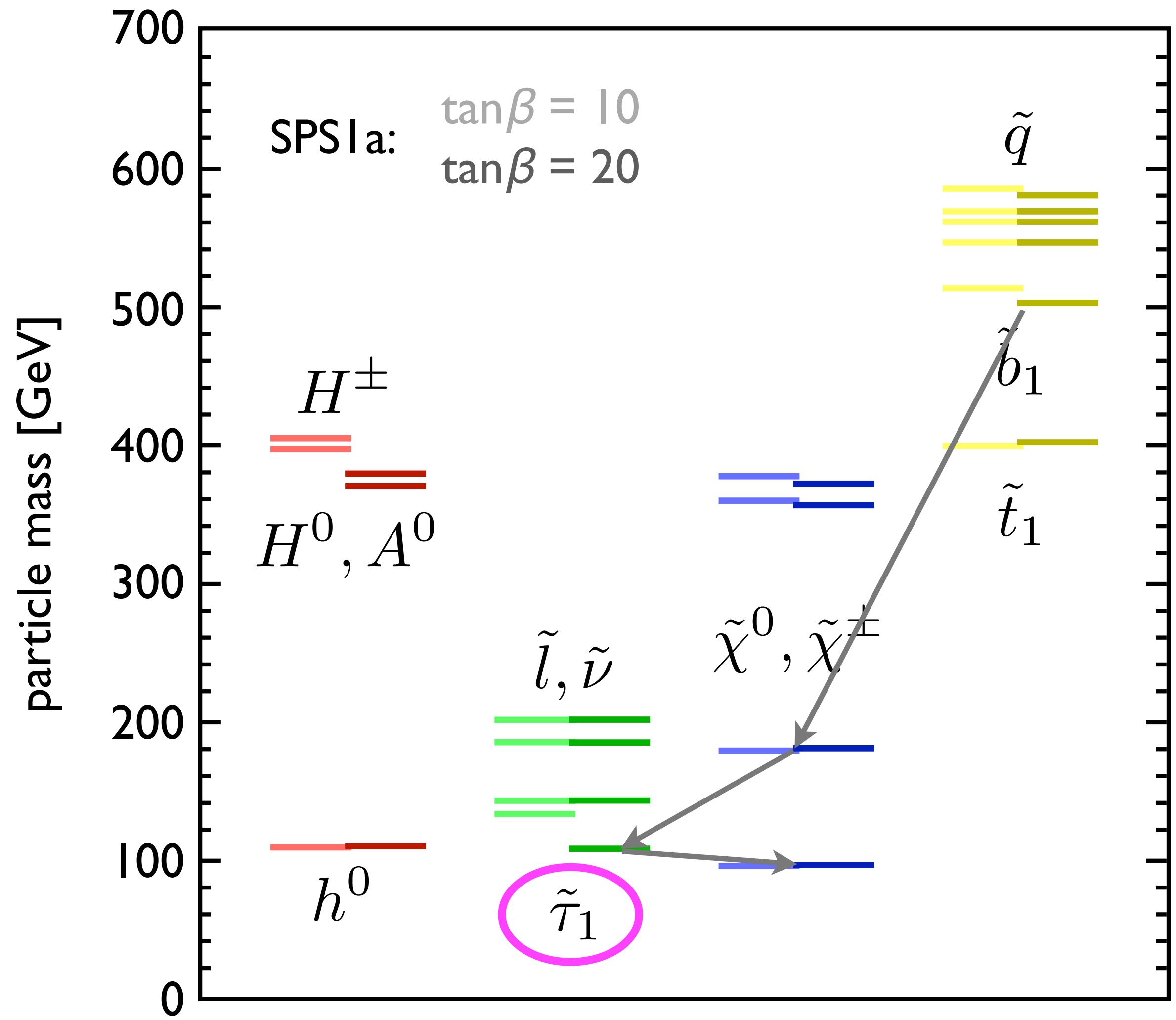
Impact on New Physics: MSSM

A gluino cascade decay chain that can be used to reconstruct mass of lightest stau at LHC

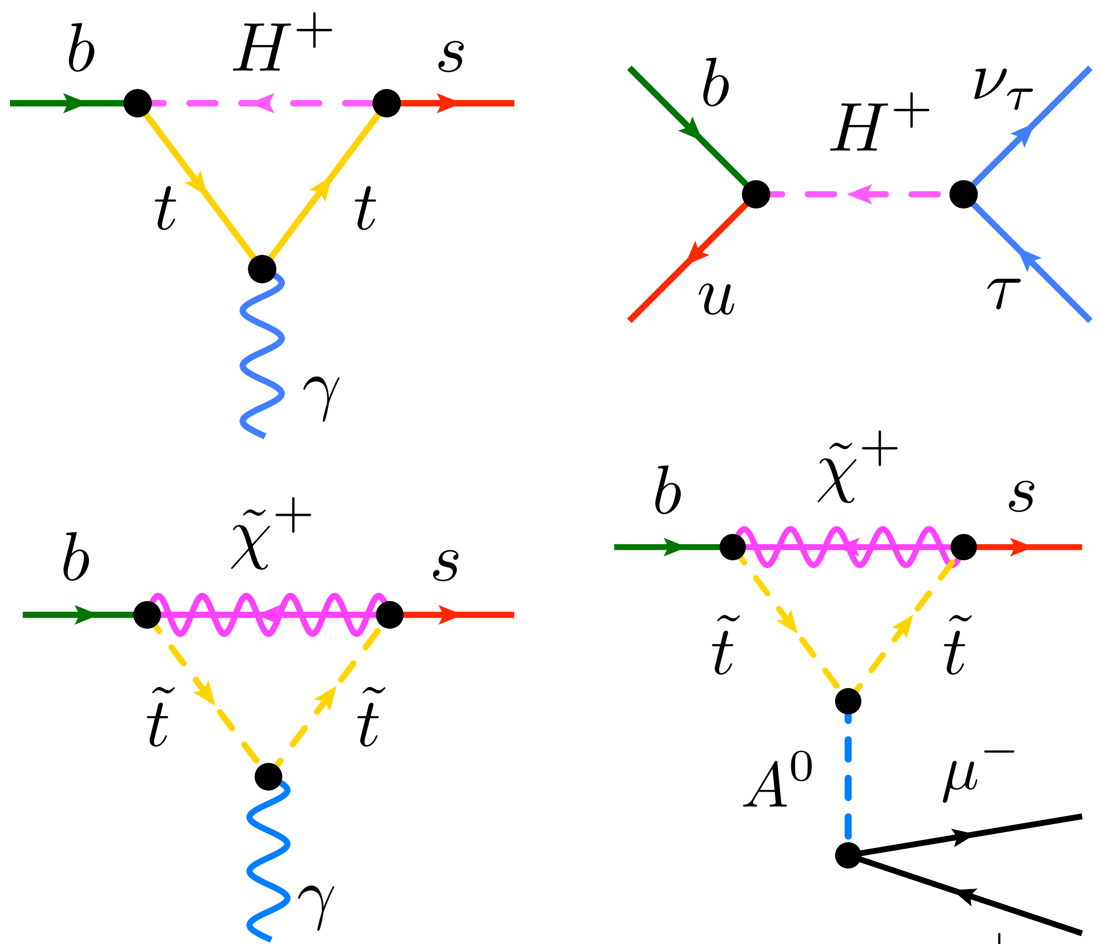




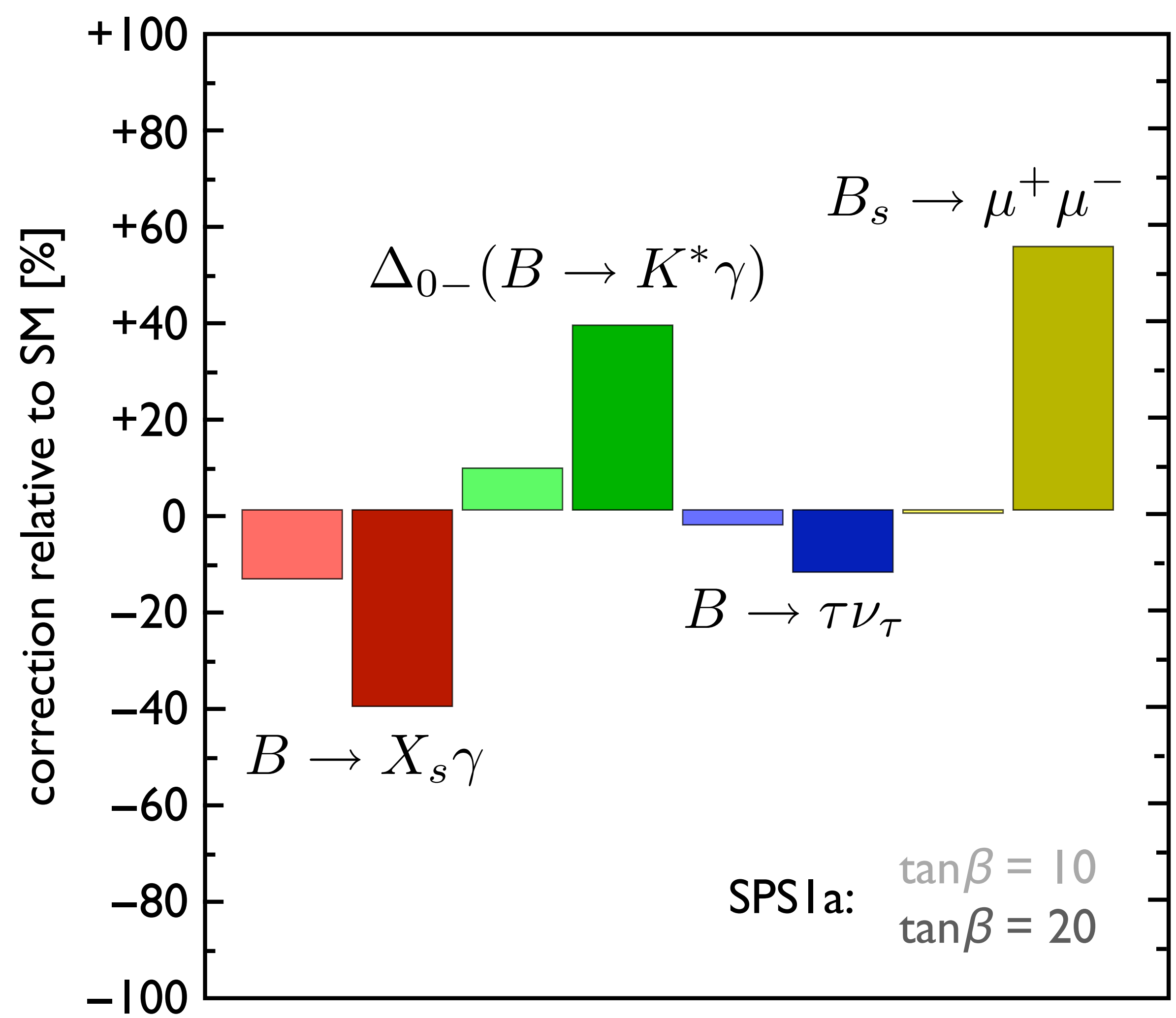
Knowing masses of gluino ($\tilde{g}$), sbottom ($\tilde{b}_1$), and neutralinos ($\tilde{\chi}^0_{1,2}$), the mass of the lightest stau ($\tilde{\tau}_1$) can be measured with precision of only 20% at LHC

LHC sensitivity to tanβ is thus typically not very large, since sparticle spectrum does not change significantly with tanβ

Impact on New Physics: MSSM



MSSM diagrams



Branching ratios of $B \to X_s\gamma$, $B \to \tau\nu_\tau$, $B_s \to \mu^+\mu^-$, and isospin asymmetry of $B \to K^*\gamma$, depend quite sensitively on tanβ

By measuring correlated shifts in these observables, it might be possible to determine tanβ with 10% accuracy, by far exceeding LHC sensitivity

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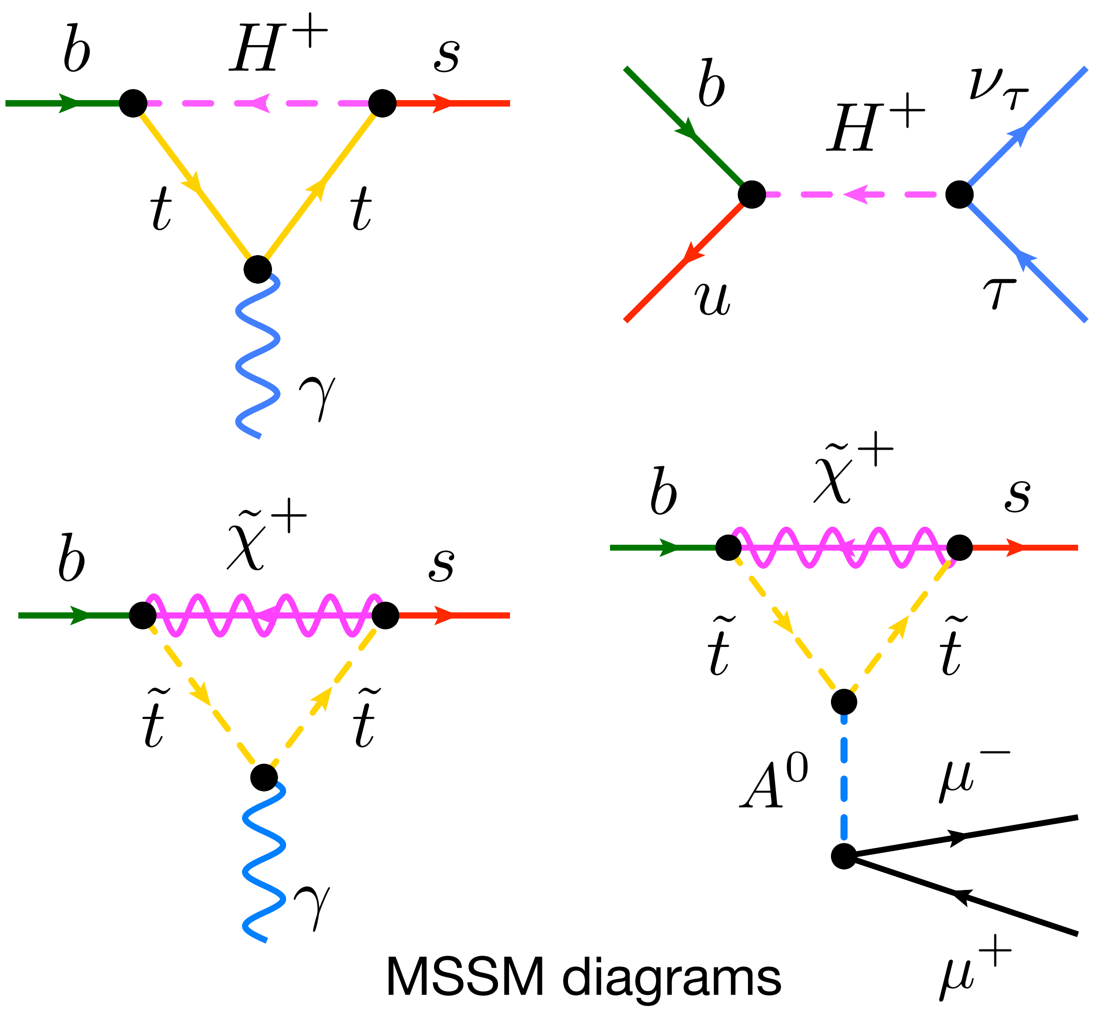
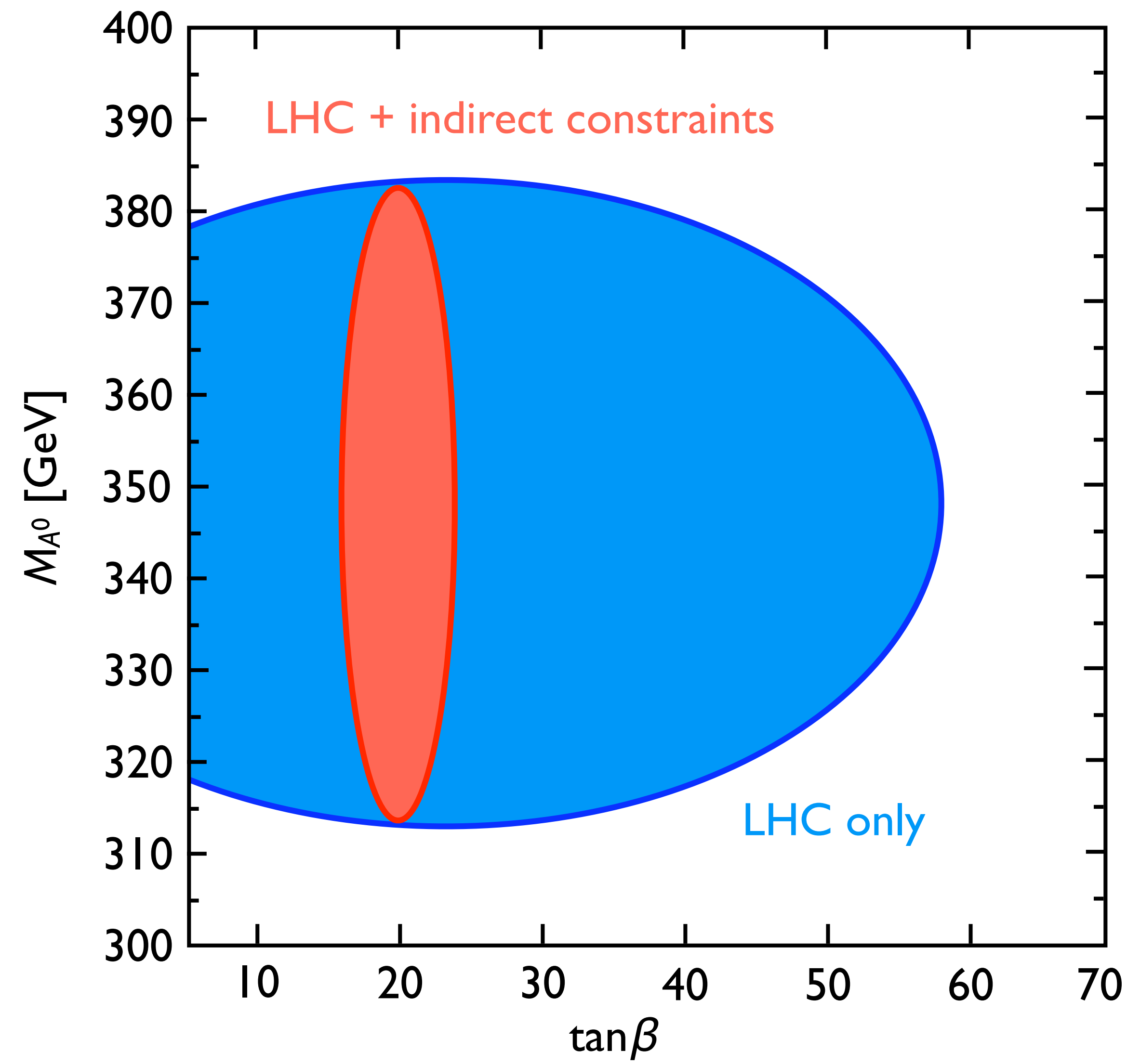
Impact on New Physics: MSSM



MSSM diagrams



Branching ratios of $B \to X_s\gamma$, $B \to \tau\nu_\tau$, $B_s \to \mu^+\mu^-$, and isospin asymmetry of $B \to K^*\gamma$, depend quite sensitively on exact value of tanβ

By measuring correlated shifts in these observables, it might be possible to determine tanβ with 10% accuracy, by far exceeding LHC sensitivity

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Puzzles in the Flavor Sector: **Facts or Fiction?**

Several observables don't look quite right ... (~2σ effects)

Puzzles in the Flavor Sector: **Facts or Fiction?**

sin2β from tree vs. loop processes

$|V_{cb}|$ and $|V_{ub}|$ exclusive vs. inclusive

$|V_{ub}|$ vs. sin2β and ε_K

$\Delta A_{CP}(B\to\pi K)$ puzzle

CP violation in B_s mixing

enhanced $B\to\tau\nu$ rate

A_{FB} asymmetry in $B\to K^*l^+l^-$

not yet measured ...

Several observables don't look quite right ... (~2σ effects)

Puzzles in the Flavor Sector: **Facts or Fiction?**

sin2β from tree vs. loop processes

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$|V_{ub}|$ vs. sin2β and ε_K

$\Delta A_{CP}(B \to \pi K)$ puzzle

Perhaps, one of these hints will solidify and point us the way beyond the SM!

CP violation in B_s mixing

enhanced $B \to \tau\nu$ rate

A_{FB} asymmetry in $B \to K^{*} l^{+} l^{-}$

not yet measured ...

Several observables don't look quite right ... (~2σ effects)

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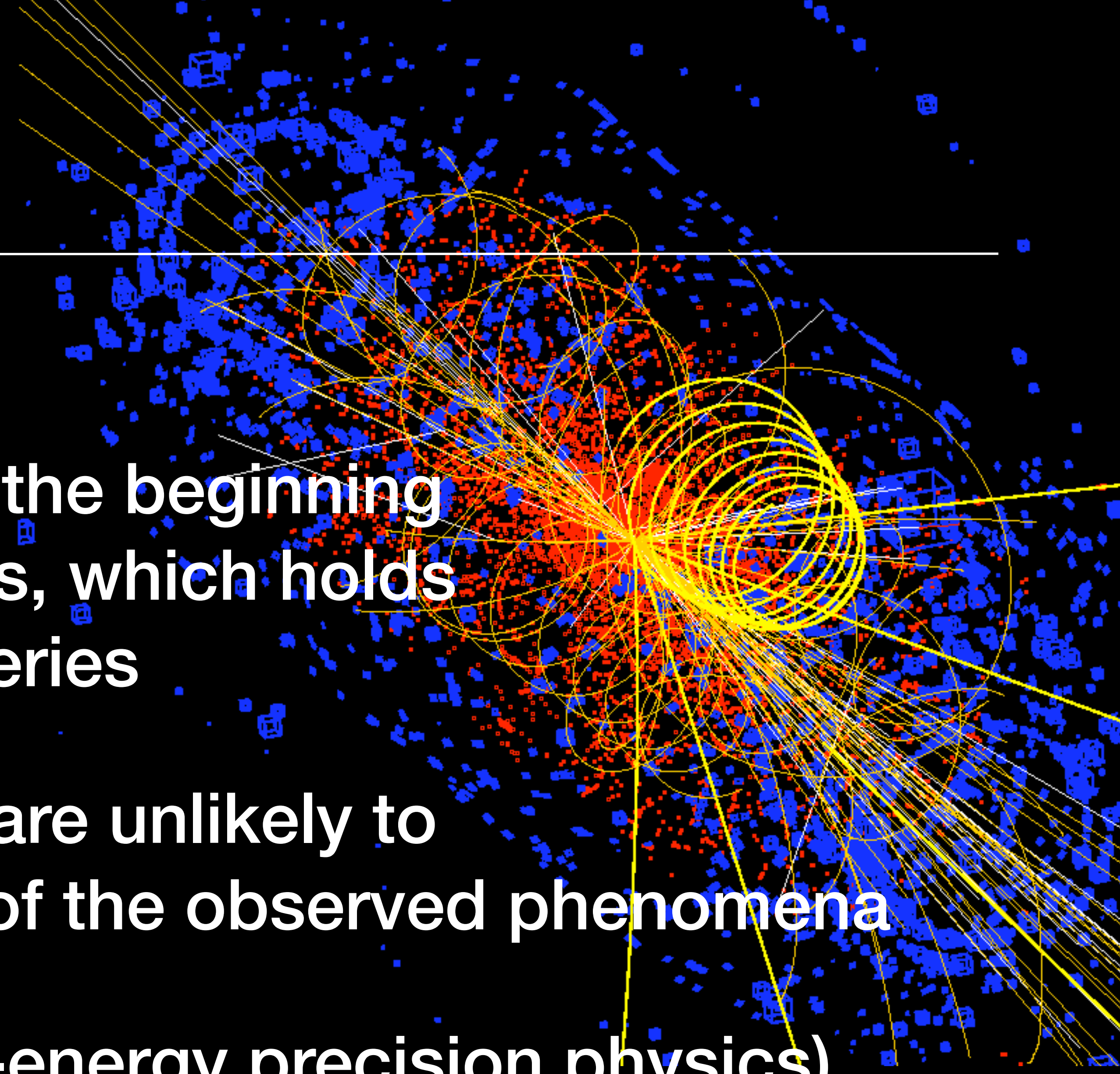
Summary and Outlook



The first collisions at the LHC mark the beginning of a fantastic era for particle physics, which holds promise of ground-breaking discoveries

ATLAS and CMS discoveries alone are unlikely to provide a complete understanding of the observed phenomena

Flavor physics (more generally, low-energy precision physics) will play a key role in unravelling what lies beyond the Standard Model, providing access to energy scales and couplings unaccessible at the energy frontier

Only the synergy of LHC and high-precision experiments may give us the key to solving the puzzles of fundamental physics